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TECHNICAL AND MICROECONOMIC ANALYSIS OF CADMIUM AND ITS COMPOUNDS

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TECHNICAL AND MICROECONOMIC ANALYSIS
OF
CADMIUM AND ITS COMPOUNDS

JUNE 1975
FINAL REPORT - TASK 1

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF TOXIC SUBSTANCES
WASHINGTON, D. C. 20460

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TECHNICAL AND MICROECONOMIC ANALYSIS
OF
CADMIUM AND ITS COMPOUNDS

June 1975

Final Report
Contract 68-01-2926, Task 1

Project Officer
David Garrett, P.E.

Prepared For
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Office of Toxic Substances
Washington, D.C. 20460

ABSTRACT

The role of cadmium (and its compounds) in the environment and in the economy of the United States was studied, to evaluate the need for and the projected effect of controlling its production, use and dissipation. Technologically and economically feasible control alternatives were developed from:

(1) A systematic documentation of cadmium production, uses, prevalence, and sources of pollution; and

(2) An evaluation of the present and projected health hazards.

Available information was then used to directly compare and optimize the various alternatives.

The results led to two sets of recommended controls. The first, aimed at preventing increases in the present cadmium health hazards, consists of continued air and water pollution abatement, environmentally-sound land disposal of industrial wastes and residuals, and regulation of application rates to agricultural lands of cadmium-bearing materials. The second set of controls exhibits a more aggressive posture towards limiting cadmium dissipation, which could be implemented in the future should a more precise definition of the health hazard justify such a posture. This second set of controls includes limitation of the cadmium impurities in products of the zinc industry, reduction in the demand for cadmium by voluntary action of several key industries and government, and the restriction or abolition of cadmium imports.

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Donald H. Sargent (Versar Inc.) and John R. Metz (Jack Faucett Associates)

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9. Performing Organization Name and Address

Versar Inc.
6621 Electronic Drive
Springfield, Virginia 22151

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Zinc Production
Cadmium Electroplating
Cadmium Pigments
Barium-Cadmium Heat Stabilizers
Nickel-Cadmium Batteries
Cadmium Microeconomics
Cadmium Control Alternatives
Cadmium in Sewage Sludge
Cadmium in Phosphate Fertilizers
Cadmium in Coal
Cadmium in Scrap Iron and Steel
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SECTION I

INTRODUCTION

Objectives of the Study

Efforts by various parts of the U.S. Environmental Protection Agency, EPA contractors, other Government agencies and other workers in the field are making increasingly apparent the present and potential dangers to man and the environment from unrestricted production and use of certain toxic chemical substances. For many of these substances, there is ample evidence of an imminent catastrophe to the general population resulting from current production and use practices. Moreover, these substances have, in general, beneficial uses and are of value to the private and public sectors of the U.S. economy. Hence, the atmosphere for regulation of these substances is neither a blanket endorsement of current and projected practices as presenting no real danger; nor is it, at the other extreme, a total and immediate ban of the production and use of these substances. Realistically, for many of these toxic substances, a careful assessment is required of the dangers, of the options reasonably available for reducing the dangers and of the economic impact resulting from implemention of such options.

This report is the result of a study specifically intended to provide such objective data for several toxic chemical substances. The substances covered in this report are elemental cadmium and cadmium compounds; subsequent reports will address other substances.

The specific objectives of this study of cadmium (and its compounds) are:

1. To objectively and quantitatively evaluate the real dangers (both present and projected) to man and to the environment, without the implementation of new and specific control measures.

2. To make an accounting of how, where, and how much cadmium is entering the environment in accessible (and possibly dangerous) forms.
3. To identify control alternatives which may be technologically and economically feasible, and to evaluate the effectiveness of each of these control alternatives in reducing the overall danger of cadmium to man and the environment.
4. To delineate the present and projected role of cadmium (and its compounds) in the U.S. economy, and to evaluate the impact of each of the control alternatives upon the economy.

Scope of This Study and Report

Much has already been published on the various aspects of cadmium and the environment. Fulkerson and Goeller(1) performed a rather complete resource analysis of the cadmium system, and their January 1973 report serves to gather and organize the information available at that time. Their work systematically covers the properties of cadmium and its compounds (physical, chemical and biological); the natural abundance and polluted levels found in air, water, and food; the estimated human dose rate ranges; the toxicology; the movement and effects of cadmium in the ecosystem; the flow of cadmium in society (i.e., in the economy); the identification of pollution sources and of abatement practices; the costs of abatement and of use restrictions; the potential for substitutes; and the control of cadmium flow in society.

In light of the breadth of the Fulkerson and Goeller report, no attempt was made in this current study to provide another (albeit newer) complete resource analysis of cadmium. Hence, this report is not intended to be an encyclopedia for cadmium, nor it is intended to provide to the reader all of the background and history pertinent to the subject. The reader is strongly urged to use the Fulkerson-Goeller report for these purposes.

In addition, the study described in this report did not have the time, funds, or mandate to generate any new experimental data to shed light on areas previously identified as needing additional research.

Reaching the overall objective (to provide an assessment of the dangers, a definition of the control options, and an evaluation of the costs and effectiveness of these options), with the previously-published work as a baseline, led to the following guidelines for emphasis in this study:

1. The critical review of previously-published analyses, where significant differences in results and interpretation of results existed.
2. The further investigation of areas pointed out by previous efforts as needing attention, and where important data has become available.
3. The investigation of areas not adequately covered in previous efforts.
4. The evaluation of new research (since the previous resource analysis), which has to some measure been spurred by the Fulkerson-Goeller effort.
5. The evaluation of the significant changes in the zinc production patterns and changes in the cadmium consumption patterns.
6. The evaluation of the very significant changes in pollution abatement practices and information available, resulting from intensive EPA efforts in the past few years.

7. The specific emphasis upon the role of cadmium in the U.S. economy.

8. The specific emphasis upon the definition of control alternatives and upon the evaluation of their respective effectiveness and economic impact.

In essence, then, this report is composed of selected areas of investigation (rather than being a complete documentation of all that is known about cadmium), leading to the discussion of the viable control alternatives. The first major part of the report (Sections IV-IX) systematically covers the important areas of cadmium production and use, the associated sources of pollution, the technology and costs for pollution abatement, the potentials for substitutions, and the control alternatives (identified but not as yet evaluated). These discussions build upon previously published analyses, and therefore include only a minimum of introductory material. The second major part (Sections X-XII) assesses the toxicology and the health hazards of cadmium and summarizes the various estimates previously made of cadmium dissipation into the environment. The third and last major part of this report (Sections XIII-XV) discusses the role of cadmium in the U.S. economy, the relative costs and effectiveness of the control alternatives, and the microeconomic impact of these control alternatives.

SECTION II

SUMMARY AND CONCLUSIONS

The table on the succeeding page is a quantitative summary of where cadmium is found, produced, converted, used, and inadvertently altered. Of the cadmium in the commercial flow in the United States, this summary table presents estimates of the amounts dissipated in end products, and of the amounts accessible to the environment via air, water, and land discharges.

The results of this study are grouped into four broad categories. First are those giving an overview of the role cadmium plays in our ecology and in our economy. The second group deals with the technologies of cadmium production, use, inadvertent appearance, and emissions. Third are the results and conclusions dealing with the industrial economics of cadmium. Last are the control alternatives deserving of further consideration.

Overview of the Role of Cadmium

1. Cadmium has unquestioned chronic toxicity leading to serious pathological consequences when ingested in quantities only 3 to 13 times greater than present average intake rates.
2. Cadmium in the soil is transported to the food chain; the cadmium concentration in plants has an approximately 1:1 relationship with the cadmium concentrations in the soil, over the entire range of concentrations down to the "unpolluted" level of 0.1 ppm.
3. It is likely that much of the cadmium dissipated by man becomes bound (in an environmentally-acceptable manner) in soil, sediment, and ocean sinks.
4. An accounting of cadmium emissions reveals that (by difference) approximately 90 per cent of the cadmium intentionally used in our economy becomes apparently immobile and is thus removed from circulation in an apparently adequate manner.

SUMMARY OF U.S. CADMIUM FLOW, DISSIPATION, AND EMISSIONS

METRIC TONS PER YEAR (1968-1972)

	Commercial Flow	Dissipations in End Products	Airborne Emissions	Waterborne Effluents	Land-Destined Wastes
In Domestic Zn Ores	2,250				
Losses in Beneficiation			0.2		250
In Domestic Zn Concentrates	2,000				
In Imported Zn Concentrates	600				
Total to Zn Smelters	2,600				
Losses in Zn Smelting			102	7	
In Zn for Galvanizing		160			
Corrosion of Galvanized Pdts.					40
Losses in Scrap Processing			0.4		12
In ZnO for Rubber		15			
Rubber Tire Wear			5.2		
Net from Zn Smelting	2,300				
In Domestic Flue Dusts	700				
In Imported Flue Dusts	400				
Domestic Cd Metal Production	3,400				
Cd Metal from GSA Stockpile	500				
Cd Metal Imports	1,700				
Total Cd Metal Supply	5,600				
Cd Metal to Electroplaters	3,100				
Losses in Electroplating				7	77
In Electroplated Products		3,000			
Losses in Scrap Processing			10		318
Cd Metal to Pigments	700				
Losses in Processing			9.5	0.8	16.5
In Plastics		675			
Losses in Incineration			6		26
Cd Metal to Heat Stabilizers	1,170				
Losses in Processing			2.7		
In Plastics		1,170			
Losses in Incineration			10		44
Cd Metal to Batteries	230				
Losses in Processing			0.7	0.3	9
In Batteries		220			
Cd Metal to Alloys & Other Uses	390				
Losses in Processing			2.3		
In Alloys, etc.		390			
Losses in Scrap Processing			2.2		20
From Phosphate Fertilizers					100
From Phosphate Detergents				10	
Collected in Sewage Sludge			20		250
From Coal Combustion			80		370
From Oil Combustion			50		
From Lubricating Oils			0.8		

5. There is a lack of definitive cause-and-effect evidence, or even of a precise analytical projection, between cadmium dissemination and chronic diseases in the United States.

6. Of the total cadmium released to the environment through the activities of man, 20 per cent is accountable to the primary non-ferrous metals industry (including ore mining and beneficiation); 30 per cent is accountable to the conversion, use, and disposition of cadmium in our economy; while the remaining 50 per cent is inadvertent (derived from fossil fuels, phosphate fertilizers, and sewage sludge) and not at all linked to the production or use of cadmium metal and its derivatives.

7. Of the total cadmium released to the environment through the activities of man, only 15 per cent is in the form of air pollution from stationary sources, and only one per cent is in the form of water pollution from point sources. These quantities appear to be decreasing, according to a comparison of 1968 emission levels with 1974-75 levels. This decrease reflects investments in abatement equipment already made and reflects the concerted efforts made by the government and private sectors to abate the readily-identifiable sources of pollution.

8. The great bulk of the total cadmium released to the environment is in the form of land-destined solid wastes, slimes, and sludges. Two categories may be defined for these materials. Less than 10 per cent of this cadmium (the first category) is in a relatively small total volume of wastes, at relatively appreciable concentrations (0.1 per cent or greater). Much of these wastes are the residuals from air and water pollution control; and there is considerable progress in either disposing of these wastes in an environmentally-adequate manner at relatively low cost or in processing these wastes to reclaim the cadmium and

other materials. More than 90 per cent of this land-destined cadmium, however, (the second category) exists in an enormous total waste volume and at relatively low concentrations (less than 0.1 per cent). These concentrations are still up to 4 orders of magnitude higher than natural cadmium concentrations in soil; the only apparently-feasible posture is the dispersing of this cadmium on our lands in the least-damaging manner.

9. While the emissions of cadmium to air and water are not expected to increase (improved pollution abatement should at least compensate for industrial growth); the release of cadmium to the land is expected to grow by 20 per cent by 1980. The primary sources of these land-destined wastes, all increasing in volume, are the combustion of coal, the use of phosphate fertilizers, the isolation of sewage sludge, and the production of steel.

Technology of Cadmium-Related Activities

1. The domestic primary zinc production capacity has shrunk significantly over the past few years, with the closing of many of the older pyrometallurgical plants. All new plants probably will be electrolytic. This trend has both reduced the emissions of cadmium from the primary zinc industry and has reduced the cadmium dissipated as an impurity in zinc and zinc byproducts.

2. Cadmium, while accounting for only 0.5 per cent of the quantity of zinc, provides approximately 5 per cent of the revenues as compared to zinc. Its financial importance to the industry, therefore, cannot be discounted.

3. The beneficiation of zinc ores is not selective with respect to cadmium. Although the cadmium in ore tailings is not at high concentrations, the cadmium quantities amount to 250 metric tons per year. The environmental mobility of this cadmium in ore tailings is not well understood, but the partial use of these tailings as an agricultural liming agent is a suspected route into the food chain.

4. The roasting of zinc concentrates usually results in very little, if any, loss of cadmium. However, when roasting is conducted at temperatures greater than 1,000°C, cadmium will be vaporized. Data for the cadmium content of the byproduct sulfuric acid (from the roasting operation) has been widely conflicting, from a range of 20 to 60 ppm previously reported by Fulkerson and Goeller,(1) to values less than 0.1 ppm newly reported by industry. A route of cadmium into the food chain, via the cadmium content of sulfuric acid used in the manufacture of phosphate fertilizers, is therefore of questionable validity.

5. Since all but two large pyrometallurgical zinc plants will be closed within the year, the wholesale release of cadmium to the air via sintering is limited to these two plants. However, they account for half of the domestic zinc capacity. The volatization of cadmium is an intentional objective of sintering; it results in the removal of 90 to 99 per cent of the cadmium in the zinc calcine. Subsequent retorting is not a large source of cadmium emissions, primarily because sintering serves to first remove the cadmium.

6. The lower grades of zinc, primarily used for galvanizing and the product of the pyrometallurgical plants, dissipate an estimated 160 metric tons per year of cadmium. Although no definitive data exists for how much of this cadmium is released to the environment, the lifetime of galvanized coatings in severe industrial or seacoast environments is as short as 4 to 12 years. Zinc may be refined to virtually eliminate this source of cadmium dissipation, but it would impart a competitive cost disadvantage to the pyrometallurgical segment of the zinc industry.

7. American Process zinc oxide has an estimated 100 ppm of cadmium as an impurity, amounting to 15 metric tons per year, primarily in rubber tires. The alternate French Process zinc oxide contains one-twentieth the cadmium.

8. Although cadmium electroplating is only a small fraction of the total metal finishing industry, it is the largest consumer of cadmium. The higher price for cadmium electroplating and the emphasis upon reducing cadmium in wastewater effluents have served to divert some of the demand to substitute metal finishes. Much of the cadmium plating is for high-quality and/or critical small parts, or in applications (military and aircraft) where firm specifications impede changes and substitutions. Significant further reductions in cadmium electroplating are unlikely in a free marketplace; conversely, a 3 per cent per year growth rate was estimated.

9. The use of cadmium pigments in plastics is expected to grow at 2 per cent per year. The relatively high price compared to other pigments has already made the demand for cadmium pigments highly selective, where no real substitutes are available. Many potential substitutes have similar toxicity problems. However, if the specific color requirements for end items were to be foregone, adequate, economical, and plentiful substitutes are available.

10. Barium-cadmium heat stabilizers for polyvinyl chloride plastics are in a reverse situation as compared to other cadmium uses. The stabilizers enjoy almost half of their market, and are the cheapest of the stabilizers; whereas cadmium in other uses is a relatively expensive and minor part of their markets. Adequate substitutes for barium-cadmium stabilizers are expected to be fully competitive from both performance and price standpoints in the near future; much substitution has already occurred. The

Food and Drug Administration is expected to broaden the end-item categories where barium-cadmium stabilizers may not be used. Because of these factors, a zero growth rate was projected for barium-cadmium stabilizers.

11. The demand for nickel-cadmium batteries is expected to grow at a rate of 15 per cent per year. Of the major uses for cadmium, only the battery end-items contain a sufficient quantity of cadmium (8 to 10 per cent) to make reclamation feasible. There already is some recycling practised, and more is expected. Several consumer products which depend upon the nickel-cadmium power source are in a rapid growth mode.

12. Two independent calculations of the quantity of cadmium involved in steelmaking (via scrap iron and steel) resulted in an estimate of 340 metric tons per year, compared to previous estimates of Fulkerson(1) and Davis(11) three times higher. Automotive scrap accounts for 75 to 85 per cent of this cadmium.

13. Although dust collection is efficient in minimizing the cadmium air emissions from steelmaking, the collected dusts contain several hundred ppm of cadmium, and thereby present an environmental hazard. However, the quantities of dusts involved are very large, and safe land disposal would amount to a large cost. Moreover, the trend in the steel industry towards decentralized, smaller capacity mills presents problems of ensuring effective air pollution control and disposition of collected dusts in a dispersed industry.

14. Recent and comprehensive data indicates that the mean concentration of cadmium in sewage sludge is 75 ppm, five times higher than the previous estimate of Fulkerson.(1) The total quantity of cadmium in sewage sludge was estimated at 300 metric tons per year, and increasing.

15. Cadmium from the combustion of coal is expected to increase rapidly as more coal is mined and used for electric power generation. Coal conversion processes offer the potential for removing and recovering cadmium.

16. Cadmium from phosphate fertilizers is expected to increase rapidly, in parallel with the growth of that industry. There are presently no means used in the United States for removing the cadmium from phosphoric acid.

Industrial Economics of Cadmium

1. The domestic production of cadmium is projected to be 4,700 metric tons per year by 1985. The domestic cadmium demand calculated as the sum of the demand for each major consuming sector, is projected to be 9,200 metric tons per year by 1985. About 40 per cent of this demand, therefore, is expected to be met by imported cadmium. The slightly higher projected demand as compared to the total projected supply would result in an increase in cadmium price by 1985 to about $11 per kilogram. The domestic consumption of cadmium is growing at 4 per cent per year.

2. The demand for cadmium, for most of the major uses and for the total, is highly inelastic (i.e., the quantity demanded is very insensitive to price). The application of a tax on cadmium sales or on cadmium imports would therefore be largely ineffective in reducing consumption.

3. A partial or total ban on cadmium use is a feasible alternative for reducing or eliminating cadmium dissipation related to its commercial use. Since cadmium is a byproduct of zinc production, its domestic supply cannot be eliminated. A partial or total ban on cadmium imports would substantially reduce its dissipative uses.

4. The costs for reducing cadmium consumption would be $16 per kilogram. The major element of these costs, for all consuming industries, is the long-run loss (ultimately paid by the many consumers of cadmium-containing products) in using substitutes which may cost more, may provide reduced quality, or may not last as long. Only the battery industry would have comparatively significant idle capital and unemployment costs.

5. A total ban on cadmium imports would result (in a free marketplace) in a cadmium price of over $20 per kilogram and in an increase in revenues to domestic cadmium producers of $40 to $50 million per year.

6. A significant reduction in the demand for cadmium electroplating might be possible through the voluntary actions of a few key consuming segments. The government (including the military), the automotive industry, the aircraft industry, the shipbuilding industry, and similar consumers are all large consumers, the prime producers are relatively few in number, they have an established prime contractor/subcontractor hierarchy, and they have a formal specification system.

7. The reclamation of used nickel-cadmium batteries should serve to significantly reduce the quantities of "new" cadmium imported into the United States, thereby directly decreasing the cadmium dissipated.

Summary of Control Alternatives

A summary of the various control alternatives, each with a concise statement of feasibility, effectiveness, and cost, is included at the end of this section. These alternatives have passed a screening process and are deserving of further consideration. Some alternatives identified in the body of this report are not included in this tabulation; some were rejected because they were not feasible, not effective, or too costly on an a priori basis; others have been amended or replaced in an optimization process.

SUMMARY OF CONTROL ALTERNATIVES

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
1	Cd electroplating, and Cd producers	Ban use of cadmium for electroplating	Most uses have substitutes; some do not	Would reduce Cd consumption by 2,700 kkg/yr now; 3,700 kkg/yr in 1985	$49 MM/yr now; $64 MM/yr in 1985.
2	Ni-Cd batteries, and Cd Producers	Ban use of cadmium for batteries	Many end-items depend on Ni-Cd power sources	Would reduce Cd consumption by 200 kkg/yr now; 1,600 kkg/yr in 1985	$24 MM first year; $10 MM/yr later; $34 MM/yr in 1985
3	Cd pigments	Ban use of cadmium for pigments	No real substitutes for many uses, except white/black pigments.	Would reduce Cd consumption by 700 kkg/yr now; 600 kkg/yr in 1985	$8 MM/yr now; $9 MM/yr in 1985
4	Cd heat stabilizers and Cd producers	Ban use of cadmium for heat stabilizers for PVC	Good-adequate substitutes should be available soon.	Would reduce Cd consumption by 1,100 kkg/yr now; 500 kkg/yr in 1985	$9 MM/yr now; $0.4 MM/yr in 1985
5	All Cd consuming industries and Cd producers	Total ban on use of cadmium	Sum of comments for alternatives 1,2,3,4	Would eliminate Cd consumption of 5,600 kkg/yr now; 9,200 kkg/yr in 1985	$115 MM first year; $101 MM/yr later; $159 MM/yr in 1985
6	All Cd consuming industries except batteries, and Cd producers	Ban use of cadmium except for Ni-Cd batteries	Sum of comments for alternatives 1,3,4	Could eliminate Cd consumption of up to 4,500-4,800 kkg/yr, but lower Cd price would discourage recycling	$63 MM/yr now; $73 MM/yr in 1985
7	Ni-Cd Batteries	Encourage recycle of Ni-Cd batteries through labeling and/or deposit system	High incentive for reclamation, some already begun	Should decrease imports by 50% in 1985	None (self-supporting)

SUMMARY OF CONTROL ALTERNATIVES (cont.)

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
8	All Cd consuming industries and Cd producers	Excise tax and equivalent import duty on cadmium		Ineffective-low demand elasticity for Cd	
9	Cd electroplating and Cd products	Seek voluntary large reduction in Cd electroplating demand by government (including military), automotive, aircraft, shipbuilding, and similar industries	Feasible because these industries are concentrated and structured	These industries account for much of Cd plating demand, reduction in Cd consumption should be much of quantities for Alternative No. 1	Corresponding fraction of costs quoted for Alternative No. 1
10	All Cd consuming industries and Cd producers	Quota on Cd metal (and flue dusts, etc.) imports, up to a complete ban on Cd imports	Higher Cd price would result; increased revenue to Cd producers would be $41MM per year now; $51MM per year in 1985	Total ban would reduce consumption to domestic production levels-3,400 kkg/yr now; 4,700 kkg/yr in 1985. Reduction would be 2,200 kkg/yr now and 4,500 kkg/yr in 1985	$33MM in first year; $22MM per year later; $60MM per year in 1985
11	Zinc ore mining and beneficiating	Regulations to control dusting from dried ore tailings with windbreaks and earth or vegetative covering	High	Reduce air emission of ~0.2 kkg/yr by >50%	Moderate
12	Zinc ore mining and beneficiating	Minimize overflow of slime ponds by requiring sizing for extreme rainfall event	High	Prevent gross discharge. Cd in slimes ~250 kkg/yr	High
13	Zinc ore mining and beneficiating	Imposing severe penalties for dam failure in slime ponds	Good-would promote effective construction, maintenance and inspection	Prevent gross discharge. Cd in slimes ~250 kkg/yr	Moderate
14	Zinc ore mining and beneficiating	Require collection and treatment of drainage from slime pond dams or tailings piles	Good	Excellent-prevents direct discharge at ~15 ppm Cd	Moderate

SUMMARY OF CONTROL ALTERNATIVES (cont.)

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
15	Primary Zinc	Continued stringent air pollution control requirements, plus continued inspection and monitoring. Maintain ≥95 % collection efficiency based upon Cd content of zinc ore concentrates	High. All plants already practise good collection (or are being closed)	Reduce Cd emissions from sintering to ~100 kkg/yr from two plants	Very high for two remaining pyrometallurgical plants, but most of investment already made
16	Primary Zinc	Promulgation of Effluent Guidelines (Water Pollution Control). Treatment and Control, and Costs, accomplish other objectives in addition to Cd removal	Demonstrated by Development Document	Reduce Cd discharge (in kkg/yr) from 10(1972) to 2(1977) to 1.3(1983)	Capital: $1.52MM (1977) + $1.05MM (1983). Annual: $0.46MM (1977) + $0.45MM(1983)
17	Primary Zinc	Regulating the land-disposal of Cd-bearing flue dusts, sludges, and other residuals.	High. The industry practices widespread reclamation of wastes	Effective safeguard against leaching or migration	Low
18	Cd Electroplating	Promulgation of Effluent Guidelines (Water Pollution Control). Treatment and Control and Costs, accomplish other objectives in addition to Cd removal	High for 1977; questionable for 1983	Reduce Cd discharge (in kkg/yr) from 10.5 (1972) to 4.0(1977) to 0(1983)	Capital: $37.5MM (1977) + $25M to $50MM(1983)
19	Cd Electroplating	Pretreatment Requirements for Wastewater, equivalent to effluent guidelines	Limited by land availability	Would reduce Cd content of sewage sludges	Included in costs for meeting effluent guidelines
20	Cd Electroplating	Regulating the land-disposal of Cd-bearing sludges	High. Also high incentive for reclamation	Effective safeguard against leaching or migration of ~80 kkg/yr Cd	$50,000 per year
21	Cd Pigments	Continued stringent air pollution control requirements, plus continued inspection and monitoring. Maintain ≥95% collection efficiency	High. All plants already practise good collection and reclaim dusts	Reduce Cd emissions to an estimated 9.5 kkg/yr	Very high, but investment already made

SUMMARY OF CONTROL ALTERNATIVES (cont.)

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
22	Cd Pigments	Promulgation of Effluent Guidelines (Water Pollution Control)	Most of industry already complies	Reduce Cd discharge to 0.75 kkg/yr	Capital: $140,000 Annual: $60,000
23	Cd Pigments	Regulating the land-disposal of Cd-bearing sludges	High. Also high incentive for reclamation	Effective safeguard against leaching or migration of ~16.5 kkg/yr Cd	$19,000/yr
24	Ni-Cd Batteries	Regulating Wastewater Discharges	High. Same treatment and control technology as other industries. Most already comply	Reduce Cd discharge to 0.3 kkg/yr	Moderate
25	Ni-Cd Batteries	Regulating the land-disposal of Cd-bearing sludges	High. Also high incentive for reclamation	Effective safeguard against leaching or migration of ~10 kkg/yr Cd	$2,700/year (1973) to $4,400/year (1983)
26	Secondary Non-ferrous Metals	Continued stringent air pollution control requirements, plus continued inspection and monitoring. Maintain ≥95 collection efficiency.	High. Much of industry already complies	Reduce Cd emissions to an estimated 2.2 kkg/yr	Very high, but investment already made
27	Secondary Non-ferrous Metals	Regulations to control dusting and wind dispersion of collected flue dusts	High. Use bin with dust control	High	Moderate
28	Secondary Non-ferrous Metals	Regulating the land-disposal of flue dusts	High. Much of industry reclaims dusts	Effective safeguard against leaching or migration of ~20 kkg/yr	Low
29	Iron and Steel	Continued stringent air pollution control requirements, plus continued inspection and monitoring. Maintain ≥95% collection efficiency	High. Much of industry complies	Reduce Cd emissions to an estimated 10.5 kkg/yr Cd	Very high, but investment already made

SUMMARY OF CONTROL ALTERNATIVES (cont.)

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
30	Iron and Steel	Regulations to control dusting and wind dispersion of collected flue dusts	High for minimills (bins) moderage for primary steel (earth cover)	High for minimills, moderate for primary steel	Moderate
31	Iron and Steel	Regulating the land-disposal of flue dusts	Very large quantities involved; incentive for reclamation	Effective safeguard against leaching or migration of ~330 kkg/yr Cd	$140MM/yr now; $220MM/yr in 1985
32	Electric Power Stations, Solid Waste Incinerators, Sewage Sludge Incinerators	Continued stringent air pollution control requirements, plus continued inspection and monitoring	High for power stations, moderate for incinerators	Reduce Cd emissions to ~120 kkg/yr	Very high
33	Phosphate Fertilizers, Sewage Treatment, Zinc Ore Mining and Beneficiating	Regulate the application rate to agricultural land of materials with Cd concentrations greater than 1 ppm. After tillage, the resulting soil should contain ≤1 ppm Cd, with variations based upon soil pH, soil type, crop type, etc.	Would require educational program, monitoring, labeling. Only moderate success expected because of diversity of users	Would limit Cd in food chain to "normal" range; intended to spread Cd dissipation over wide areas	Moderate
34	Coal Gasification and Liquefaction	Develop effective Cd removal and recovery technologies as integral part of coal conversion processes; highlight fate of Cd in EIS; develop regulations as technology emerges	High, since most coal conversion R&D is government sponsored	Moderate, because of Cd volatility. Should recover ≥ 75% of Cd with control of particulates	Moderate increment to total cost of coal conversion
35	Phosphate Fertilizers	Sponsor and encourage research aimed at Cd removal and recovery in the manufacture of phosphoric acid	Possibility using solvent extraction techniques	Would prevent Cd dissipation directly to food chain	Possibly high compared to price of fertilizers
36	Phosphate Fertilizers, Primary Zinc	Banning the use of sulfuric acid with ≥2 ppm Cd for manufacturing fertilizers	High. Much H_2SO_4 is not smelter-gas acid.	Would divert any high-Cd acid to other uses	Low

SUMMARY OF CONTROL ALTERNATIVES (cont.)

No.	Industry Segment Affected	Control Alternative	Feasibility	Effectiveness	Costs
37	Primary Zinc, Lead, Copper	Regulating the Cd concentration of byproduct sulfuric acid from zinc, lead, and copper ores to ≤2 ppm	High. Two companies have <2 ppm Cd in sulfuric acid	Would recover virtually all Cd, not just divert its use	Moderate
38	Primary Zinc	Regulating the Cd concentration of zinc oxide (and other zinc compounds) to ≤10 ppm	Would require change to French Process; involves inequity	Would stop dissipation of ~15 kkg/yr Cd in ZnO	High
39	Primary Zinc	Regulating the Cd concentration of all zinc metal to ≤40 ppm	Involves inequity	Would stop dissipation of ~160 kkg/yr Cd in Prime Western zinc	$9MM/yr

SECTION III

RECOMMENDATIONS

There appear to be sufficient grounds, on the basis of potential health hazards, for prudent measures to be taken to prevent any large increases in the dissipation of cadmium in our environment; to reduce or eliminate those discharges which are readily identifiable and potentially controllable; to carefully monitor the movement of cadmium in our ecology; and to support further research aimed at both quantifying the problem and developing ways to ameliorate the problem.

However, in light of the lack of definitive cause-and-effect evidence between cadmium dissemination and chronic diseases in the United States, the lack of evidence that ingested cadmium is increasing, the likelihood that much of the dissipated cadmium becomes bound in soil, sediment and ocean sinks; the indication that much progress is being made in air and water pollution abatement; and the fact that half of the man-made dissipation of cadmium is not at all related to the cadmium producing and using industries; no urgent program of bans on cadmium production, imports, or use is justified at this time.

We are faced with the dilemma that if the projections of this study are qualitatively valid, the quantities of cadmium dissipated are increasing at a substantial rate. It is therefore not possible to prevent cadmium proliferation by simply maintaining our present posture.

In response to this dilemma, we recommend one set of control measures deemed prudent for the present, and another set of control measures which may be implemented in the future should new data justify a more aggressive control posture.

Control Alternatives Recommended for the Present

A. Continued promulgation and enforcement of stringent regulations for air pollution abatement from stationary sources and for water pollution abatement from point sources. The specific control alternatives recommended, referring to the tabulation in Section II, are numbers 11, 12, 13, 14, 15, 16, 18, 19, 21, 22, 24, 26, 27, 29, 30, and 32.

B. Promulgation and enforcement of regulations for ensuring that cadmium-bearing industrial wastes destined for land disposal be treated and disposed of in environmentally adequate ways. The specific control alternatives recommended, referring to the tabulation in Section II, are numbers 17, 20, 23, 25, and 28. Control alternative 31 (for the iron and steel industry), while falling into this category, is associated with extremely high costs; further information is needed regarding the technology and costs of treating these flue dusts for the removal of cadmium.

C. Regulation of the application rate to agricultural lands of cadmium-bearing fertilizers, sewage sludges, zinc ore tailings, and solid wastes from combustion and incineration processes (control alternative number 33). Further efforts are needed to precisely define the limitations and the variations of limitations.

D. Encouragement of research for the removal of the cadmium impurity in fertilizers and coal (control alternatives 34 and 35).

E. Encouragement of the reclamation of cadmium, primarily from used nickel-cadmium batteries. (Control alternative 7).

F. Encouragement of continued research and monitoring to define with greater precision the health hazards presented by cadmium.

Control Alternatives Recommended for the Future

Should further research and monitoring provide justification in terms of definitive health hazards for more aggressive control measures, and should new data verify the projections of this study that cadmium dissipation will increase, then the following control alternatives could be adopted after more detailed evaluation:

A. Regulation to very low levels of the cadmium impurity in products and byproducts of the primary zinc industry (control alternatives 37, 38, and 39).

B. Reduction in the demand for cadmium, through voluntary actions of major consumers, starting with the federal government (control alternative 9).

C. Restriction on cadmium imports, the quota to be determined by assessing the severity of the problem; and imposing a total ban on imports as an extreme measure (control alternative 10).

SECTION IV

PRIMARY ZINC INDUSTRY

Cadmium occurs naturally in zinc ores (and in lead-zinc and copper-lead-zinc ores) in the approximate ratio of one part of cadmium to 200 parts of zinc. As such, and because there is no separate ore of cadmium, these zinc ores are the sources for primary cadmium, either as a byproduct in the recovery of primary zinc or in the processing of the residuals from the recovery operations for other metals.

Cadmium occurs wherever zinc is found. The average worldwide abundance of cadmium and zinc, respectively, are 0.18 ppm and 80 ppm, for a Cd/Zn ratio of 0.23 per cent.(1) In zinc ores and lead-zinc ores, the Cd/Zn ratio averages 0.5 per cent, according to Fulkerson,(1) Page,(2) and Hallowell.(3)

The zinc ores, lead-zinc ores, and copper-lead-zinc ores are processed by several methods, primarily flotation and heavy-media separation, to produce a zinc concentrate which may contain 49.0 to 53.6 per cent zinc and 0.24 per cent cadmium (for a Cd/Zn ratio of 0.47 per cent).(3) Five zinc ore concentrates sampled by Yost (4) had an average Cd/Zn ratio of 0.31 per cent. Other published data for zinc concentrates are listed in Table 1.

These data show that while 0.50 per cent may be a representative value for the Cd/Zn ratio, there is significant variation around this value for individual ores and concentrates. Hence, to analyze the fate of cadmium in the mining, beneficiation, and recovery of zinc, material balances must be made upon individual operations rather than upon aggregate values.

Ore Beneficiation

The zinc ores (and lead-zinc ores) that are processed are, of course, mostly gangue, which is principally dolomite with minor amounts

TABLE 1

COMPOSITION OF ZINC CONCENTRATE

SOURCE: AIME(5)

Zinc Producer	Per Cent Zn	Per Cent Cd	Cd/Zn, %
Canadian Electrolytic	53.4	0.27	0.51
Allied (Canada)	52.5	0.11	0.21
Mitsubishi (Japan)	51.8	0.21	0.40
American Zinc Co.	54.55	0.40	0.73
Espanola del Zinc	50.50	0.20	0.40
N.J. Zinc Co.	52	0.22	0.42
St. Joe Minerals	56.0	0.22	0.39
St. Joe Minerals	52.0	0.25	0.48
St. Joe Minerals	54.0	0.35	0.65
Broken Hill (Australia)	51.0	0.21	0.41
Broken Hill (Australia)	53.7	0.22	0.41
Broken Hill (Australia)	52.1	0.20	0.38
Broken Hill (Australia)	52.9	0.18	0.34

of calcite present. The extremely fine interlocking distribution of the sphalerite (the zinc sulfide ore) necessitates grinding to typically 90 per cent minus 200 mesh to liberate the sphalerite so that it may be separated from the gangue. Typical material balances for ore beneficiation (based upon 1000 units of ore heads) are listed in Table 2.

Three important observations may be made from these data:

1. The cadmium/zinc ratio does not change as a result of beneficiation; i.e., the cadmium in the ore is carried quantitatively with the zinc to the lead concentrate, the zinc concentrate and the residue:

Ore	Broken Hill BHS	Broken Hill BHN	Broken Hill ZC
Cd/Zn, Per Cent:			
Ore Heads	-	0.42	0.36
Pb Concentrate	0.50	0.43	0.31
Zn Concentrate	0.41	0.42	0.38
Residue	-	0.47	-

2. The beneficiation does a rather effective job from a process engineering viewpoint of removing the zinc (and so the cadmium), so that the residue has a very low quantity of zinc and cadmium by comparison with the original ore:

Ore	Zn Content of Tailings, %
Ozark (5)	0.16
Broken Hill Avg. (5)	1.02
Average (1)	0.27
Average (7)	0.18
Average (6)	0.38

TABLE 2

MATERIAL BALANCES FOR ZINC ORE CONCENTRATION

SOURCES: ORNL,(1) AIME(5)

Ore	Ozark Lead Co.(5)	Broken Hill BHS(5)	Broken Hill BHN(5)	Broken Hill ZC(5)	ORNL Avg.(1)
Ore Heads, Total	1000.0	1000.0	1000.0	1000.0	1000.0
Lead	55.1	102.0	134.0	115.0	40.0
Zinc	10.7	96.0	109.8	100.0	30.0
Cadmium	-	-	0.459	0.36	-
Lead Conc., Total	73.7	136.1	175.5	145.3	62.8
Lead	53.2	97.5	130.1	110.9	37.6
Zinc	1.5	6.0	8.1	5.1	-
Cadmium	-	0.030	0.035	0.016	-
Zinc Conc., Total	15.2	160.4	180.7	170.0	55.2
Lead	0.6	1.9	1.2	1.4	-
Zinc	7.7	82.8	97.5	88.5	27.6
Cadmium	-	0.337	0.405	0.340	-
Residue, Total	911.1	703.5	643.8	684.7	882.0
Lead	1.3	2.7	2.7	3.0	2.4
Zinc	1.5	7.0	4.0	9.9	2.4
Cadmium	-	-	0.019	(0)	-

3. The quantity of tailings is of the same magnitude as the quantity of ore heads, since only a minor quantity is removed as concentrates. The annual quantity of tailings from U.S. mines is 16,750,000 kkg.(1)

While the mine overburden usually contains less than 50 ppm cadmium,(1) the tailings contain only about 15 ppm cadmium as 0.5 per cent of a zinc content of 0.3 per cent). From a process engineering viewpoint, therefore, it appears that the removal of cadmium from the land-destined tailings has been entirely adequate.

However, from an environmental viewpoint, the adequacy is highly suspect. The level of cadmium in the tailings, 15 ppm, is two orders of magnitude greater than the average crustal abundance, although it is obviously of the same magnitude as the soil in the mine vicinity. The environmental problem is that these tailings have become mobilized in the environment as a result of the grinding, hydroclassifying, and flotation operations (as opposed to their previous dormant state in nature where they were locked into the gangue matrix). The mobility of the tailings is a result of the very fine particle size, 86 per cent at minus 325 mesh,(7) and of the physical state as a slime. As with most slime ponds, the dried fines tend to dust during windy weather. Abatement techniques in use in the United States include spraying with water or soil covering to minimize dusting. Trees have been planted around the ponds to act as windbreaks, and vegetative coverings have been planted. Another potential environmental hazard is occasional release of slimes during periods of heavy rainfall by overflowing of the banks of the ponds; no pond in a climate with a positive rainfall/evaporation balance can be designed to accomodate all storms without overflows. Accidental breaks of earthen dams containing slime ponds may result in huge losses to the environment. The cadmium content of a zinc ore tailings pond effluent was found to be 0.0 to 0.02 mg/l.(3) An EPA-sponsored effort to develop effluent limitations guidelines for zinc ore mining and processing is nearing completion, and more definite data on the waterborne cadmium losses should become available.

There has been considerable utilization of tailings in the United States for road stone (particularly the coarse fractions), for railroad ballast, as an asphalt filler and as mortar sand. Since the domestic tailings are dolomitic (typically 30 per cent CaO, 18 per cent MgO and 10 per cent SiO_2) and contain trace elements, agricultural uses as a liming agent and soil conditioner have been relatively popular for tobacco, cotton and peach growing.(6,7,15) In 1971, 23 per cent of the domestic zinc ore was mined in Tennessee(8), so that the tailings were geographically situated for use on these crops. Additional data is needed to determine whether any correlation exists between the use of zinc ore tailings as agricultural lime and the surprisingly high cadmium levels found in tobacco, peanuts, and beet pulp.(9)

The mobility of cadmium in an aqueous system is highly dependent upon pH. Cadmium carbonate is relatively insoluble in alkaline waters (such as would be expected with the associated dolomite). However, if ammoniacal fertilizers are used, there is a danger of dissolved cadmium resulting from the formation of the soluble cadmium-ammonia complex ions, $Cd(NH_3)_2^{+2}$ and $Cd(NH_3)_4^{+2}$.

The total cadmium in domestic mine tailings may be estimated at 250 metric tons per year (at 15 ppm). Only a portion, however, is released to the environment. While quantitative data on this fraction is not available, evidence that it is significant at least in some cases is the cadmium content of surface waters downstream of beneficiation sites. The most prominent instance has been the Jintsu River in Japan, the site of the infamous Itai-Itai disease. Upstream of the zinc mine, the bottom sediments contained less than 0.2 ppm cadmium; downstream, the cadmium content of the sediment measured 238 ppm. The downstream Jintsu River water contained 1 to 9 μg/l cadmium, not unusual for natural waters in zinc-bearing formations, indicating either that the cadmium pollution was in the form of suspended solids or that the sediments adsorbed and accumulated the cadmium from the water (as is typical of such sediments).(2,4) Other reported instances of very high cadmium concentrations in surface waters near zinc mines include the Coeur d'Alene River in Idaho, where 450 μg/l was measured by USGS.(1,2) In comparison, the proposed EPA toxic pollutant effluent standards for cadmium are based upon a fresh-water receiving body concentration after mixing of 0.24 μg/l (cronic) and 4.0 μg/l (acute).(10)

The release to the air of ore tailing dusts was estimated by Davis as one part of cadmium for each 10,000 parts of cadmium in the ore.(11) Since it was previously shown that only about 10 per cent of the cadmium in the ore winds up in the residue, the Davis emission factor is an air loss from tailings of one part per thousand. This is equivalent, then, to an air emission in the U.S. of 0.25 kkg per year of cadmium.

In summary, then, the mine tailings may constitute a real hazard due to the mobility of the wastes. Although quantitative data on this mobility are not available, evidence of the results of this mobility at several sites has been reported in terms of cadmium pollution of surface waters.

It should be emphasized that at this point, little quantitative information exists for the mobility of the tailings in the environment. It appears that technology for minimizing the release of cadmium from zinc ore tailings to the environment does exist, and in fact, is practised to a large extent. The regulatory options include:

1. Limiting the cadmium content of the wastewater effluent from the slime ponds (which the proposed toxic guidelines would do). If the cadmium content of the tailings is 15 ppm, the chronic limitation of 0.24 μg/l is equivalent to a total suspended solids limitation of 16 mg/l in the effluent, without counting any cadmium contribution as dissolved solids. Such a 16 mg/l suspended solids regulation

is marginally attainable with settling pond technology; it may require polishing filter technology.

2. Requiring that slime ponds be sized for a severe storm situation, perhaps for a 10-year, 24-hour rainfall event, to minimize the frequency of overflowing.
3. Requiring that any effluent resulting from an excess of precipitation over evaporation be treated before discharge. Lime treatment and settling should result in a total cadmium concentration of no more than 0.5 mg/1.(8,12)
4. Imposing extremely stiff penalties for failure of slime pond dams, which would encourage industry to effectively construct, inspect and maintain these dams.
5. Requiring that drainage from existing and future tailings piles be collected and treated, rather than be allowed to discharge directly into ground waters or into surface waters.
6. Imposing regulations for the effective control of dusting from the dried tailings, such as earth covering, vegetative covering, and windbreaks.
7. Restricting the use of tailings for agricultural purposes especially, and perhaps for road and railroad bed purposes. The agricultural restrictions may involve application as well as distribution; so that the cadmium content of soils after tilling is within the normal range and so that

concurrent application of ammonia fertilizers does not lead to solubilization of the cadmium. If, in fact, there is a cause-and-effect relationship between the use of tailings as high-cadmium aglime and the high cadmium content of tobacco (as has yet to be demonstrated), then a ban of this use should be considered owing to the high retention by the human body of cadmium in cigarette smoke.

U.S. Production of Zinc Ore Concentrates and Slab Zinc

The domestic production of zinc ore concentrates and of slab zinc have been decreasing, in relation to the rest of the free world, in a rather dramatic fashion, as is shown in Table 3.

Since cadmium production is intimately tied to zinc production, these drastic changes in zinc demand a very thorough update of previous cadmium material balances.

Prior to 1964, U.S. smelter capacity exceeded U.S. zinc consumption, and we were a net exporter of zinc. The U.S. imported large quantities of zinc concentrate as feedstock for domestic production essentially matched the domestic consumption. However, domestic smelter closings since 1968 have caused a widening gap, to the point where the U.S. is a significant net importer of zinc. It appears that the U.S. metal production has shrunk to the point where it can service the domestic mine production of concentrates.

The main driving force for domestic contraction has been the rapid growth of foreign consumption of zinc. In 1950, the U.S. consumed 50 per cent of the free world's zinc supply. Between 1950 and 1970, the U.S. consumption grew at a rate of only 1.6 per cent, compared to 4.4 per cent in Europe, 13.7 per cent in Japan, and 7.2 per cent in the rest of the free world. Consequently, the U.S. consumption in 1970 was only 30 per cent of the free world total. Since the U.S. always had to import ore

TABLE 3

TREND OF DOMESTIC ZINC ORE AND METAL PRODUCTION

SOURCES: AIME,(5) ENGINEERING AND MINING JOURNAL,(13)
BUREAU OF MINES,(14,15) GEOLOGICAL SURVEY(16)

Year	U.S. Mine Production (Zn content)		U.S. Metal Production (Primary Zinc)	
	kkg	% of free world	kkg	% of free world
1952-56	497,800	21.2	888,100	41.5
1958	410,700	16.9	751,000	33.8
1968	527,800	13.6	982,700	27.4
1969	501,000	12.2	944,000	24.8
1970	484,000	11.5	796.000	22.0
1971	456,000	10.6	695,000	20.2
1972	433,000	10.1	574,000	15.1
1973	432,000	10.0	491,000	(13.2)
1974	446,000		490,000	

concentrates, the domestic competitive position deteriorated as its share of demand decreased and as foreign metal production capacity increased.

Two other major factors contributed to the domestic decline in zinc production. One has been the expensive pollution control equipment demanded recently for older smelters, and the other has been the high production cost of the older labor-intensive domestic smelters. Table 4 lists the domestic zinc plants by process, with production capacities and age. It is apparent from Table 4 that:

1. Until the new New Jersey Zinc plant (now under construction) comes on stream, the newest plant in the U.S. is 33 years old.
2. A rash of recent plant closings has accounted for the drastic decrease in domestic zinc production.
3. Older pyrometallurgical plants, especially horizontal retort plants, are closing because they are labor-intensive, because they have severe air pollution problems, and because they cannot manufacture the high grades of zinc. Only two small U.S. horizontal retort plants are still in operation, and account for only 13 per cent of the total U.S. production capacity of 689,000 metric tons per year. The two large pyrometallurgical plants (one vertical retort plant and one electrothermal plant) account for 48 per cent of the U.S. capacity, and the three electrolytic plants account for the remaining 39 per cent.

The following distribution of the free-world zinc manufacturing processes also illustrates the recent widespread closings of horizontal

TABLE 4

U.S. ZINC PLANTS

SOURCES: AIME,(5) EPA,(8) ENGINEERING AND MINING JOURNAL,(13)
AMERICAN METAL MARKET(17)

Company	Location	Process Types			Annual Capacity, kkg	Year Opened	Year Closed
		Roast	Sinter	Reduction			
ASARCO	Amarillo, Tex.	Mult. Hearth	Down Draft	Horiz. Retort	42,000	1923	-
AMAX	Blackwell, Okla.			Horiz. Retort	(73,000)	1916	1973
National Zinc	Bartlesville, Okla.	Fluid Bed	Down Draft	Horiz. Retort	45,000	1907	-
American Zinc	Dumas, Tex.	Mult. Hearth	Down Draft	Horiz. Retort	(53,000)	1940	1971
Eagle Picher	Henryetta, Okla.	Fluid Bed	Up Draft	Horiz. Retort	(50,000)	1916	1969
N.J. Zinc	Palmerton, Pa.	Flash		Vert. Retort	103,000	1899	-
N.J. Zinc	Depue, Ill.	Fluid Bed		Vert. Retort	(64,000)	1906	1971
Mattheissen & Hegeler	Meadowbrook, W.Va.	Fluid Bed		Vert. Retort	(41,000)	1911	1971
ASARCO	Corpus Christi, Tex.	Flash, Fl. Bed	-	Electrolytic	98,000	1941	-
American Zinc	E. St. Louis, Ill.	Fluid Bed	-	Electrolytic	(76,000)	1941	1971
Anaconda	Great Falls, Mont.	Fluid Bed	-	Electrolytic	(147,000)	1915	1972
Anaconda	Anaconda, Mont.	Fluid Bed	-	Electrolytic	(82,000)	1928	1969
Bunker Hill	Kellogg, Ida.	Flash	-	Electrolytic	110,000	1928	-
St. Joe Mineral	Monaca, Pa.	M.H., F.B.	-	Electrothermic	227,000	1938	-
AMAX	E. St. Louis, Ill.	Fluid Bed	-	Electrolytic	(64,000)	1975	-
N.J. Zinc	Clarksville, Tenn.			Electrolytic	(145,000)	1977	-

retort plants: (5,13)

Process	Year of Commercial Adaptation	Pct. of Total Production	
		1958	1970
Horizontal Retort	1800	32%	15%
Electrolytic	1915	50%	56%
Vertical Retort	1930	7%	10%
Electrothermic	1936	3%	7%
Imperial Smelting	1950	8%	12%

The two critical points to be emphasized, with respect to this drastic change in the domestic zinc production picture, are:

1. The decreases in U.S. zinc production reduce the release of cadmium to the environment in the U.S. resulting from zinc production,
2. The replacement of "dirty" retorting with "clean" electrolytic plants results in less cadmium release to the environment during zinc production, in less cadmium content of the product zinc, and in a potentially greater supply of primary cadmium.

With these dramatic changes in mind, the zinc recovery processes will be reviewed from the standpoint of the fate of the cadmium in the ore concentrates.

Zinc Recovery from Ore Concentrates

All domestic zinc plants subject the ore concentrate to a roasting process, to convert the zinc sulfide to the oxide (and some sulfate). Roasting prior to pyrometallurgical zinc recovery is geared to remove a maximum of the sulfur in the concentrate, while roasting prior to hydrometallurgical (i.e., electrolytic) zinc recovery is tailored so that a controlled amount of zinc sulfate may be produced.

Three methods of roasting are in use: a multiple-hearth furnace, a flash roaster, and a fluid-bed roaster. Table 5 lists the relative metal content of feed and product for several specific roasting operations (it was previously pointed out that because of variations in the cadmium content of concentrates, aggregate data has limited value). Also listed in Table 5 are the ratios of cadmium to zinc in the feed and product; and the ratios of cadmium to zinc in the feed and product; and the ratios of Zn, Cd, Pb, and Cu to Fe in the feed and product. This latter set of ratios was calculated because iron (and its compounds) is the least volatile and because iron is present in appreciable quantities; hence, it is used in this analysis as a tracer material. Finally, the feed/product ratios of the metal ratios are shown in Table 5.

From these last sets of ratios, a set of statistics was calculated to determine if these ratios were significantly different from unity; i.e., if there was significant loss of any metal relative to other metals. (The last three columns of Table 5 were not included in this set of statistics, for reasons explained below.)

Feed/Product Ratio	No. Data Points	Average, $\overline{R}$	Std. Dev., S
Cd/Zn	8	1.02	0.11
Zn/Fe	7	0.96	0.05
Cd/Fe	7	1.02	0.05
Pb/Fe	4	0.93	0.15
Cu/Fe	6	0.99	0.02

These data show that the roasting process does not result in any significant loss of cadmium relative to zinc, nor of any of the more volatile metals relative to iron.

TABLE 5

METAL CONTENT OF ROASTER FEED AND PRODUCT

SOURCES: YOST,[4] AIME[5]

Plant		N.J. Zn Palmerton (4)	Canadian Elect. Zn (5)	Allied, Canada (5)	Akita, Japan (5)	American Zinc (5)	Espanola Del Zinc (5)	Espanola Del Zinc (5)	N.J. Zinc Depue (5)	St. Joe H.G. (5)	St. Joe Int. (5)	St. Joe P.W. (5)
Type of Roaster Temp., °C		Flash -	Fluid 900	Fluid 900	Fluid 930	Fluid 950	M.H. -	Fluid 1,000	Fluid 1,000	Flash, Fluid 950	Flash, Fluid 950	Flash, Fluid 950
Metals in Ore Conc. (Feed), %	Zn	54	53.4	52.5	51.8	54.55	49.30	49.30	52	56.0	52.0	54.0
	Cd	0.16	0.27	0.11	0.21	0.40	0.15	0.15	0.22	0.22	0.25	0.35
	Pb	0.50	-	-	1.3	0.68	1.00	1.00	0.65	0.50	0.30	0.30
	Cu	-	0.62	0.38	0.72	0.58	0.15	0.15	-	0.25	0.25	0.40
	Fe	-	10.1	10.4	8.1	5.64	12.30	12.30	10	5.0	7.8	7.0
Metals in Calcine (Product), %	Zn	67	61.4	59.4	59.7	62.97	56.75	56.05	58.5	68.0	64.0	62.0
	Cd	0.25	0.31	0.12	0.23	0.47	0.14	0.15	0.25	0.22	0.25	0.40
	Pb	0.74	-	-	-	0.79	1.25	1.25	0.65	0.035	0.035	1.4
	Cu	-	0.74	0.45	0.81	0.67	0.15	0.15	-	0.26	0.26	-
	Fe	-	11.6	11.8	9.2	6.51	12.75	12.25	11	6.0	9.5	7.3
Ratios in Feed, %	Cd/Zn	0.30	0.51	0.21	0.41	0.73	0.30	0.30	0.42	0.39	0.48	0.65
	Zn/Fe	-	518	504	639	969	401	401	520	1120	667	771
	Cd/Fe	-	2.7	1.1	2.6	7.1	1.2	1.2	2.2	4.4	3.2	5.0
	Pb/Fe	-	-	-	16	12.1	8.1	8.1	6.5	10.0	3.8	4.3
	Cu/Fe	-	6.1	3.7	8.9	10.3	1.2	1.2	-	5.0	3.2	5.7
Ratios in Product, %	Cd/Zn	0.37	0.50	0.20	0.39	0.75	0.25	0.27	0.43	0.32	0.39	0.65
	Zn/Fe	-	529	503	650	967	445	458	531	1130	674	850
	Cd/Fe	-	2.7	1.0	2.5	7.2	1.1	1.2	2.3	3.7	2.6	5.5
	Pb/Fe	-	-	-	-	12.1	9.8	10.2	5.9	0.58	0.37	19
	Cu/Fe	-	6.4	3.8	8.8	10.3	1.2	1.2	-	4.3	2.7	-
Feed Ratio / Product Ratio	Cd/Zn	0.81	1.02	1.05	1.05	0.97	1.20	1.11	0.98	1.22	1.23	1.00
	Zn/Fe	-	0.98	1.00	0.98	1.00	0.90	0.88	0.98	0.99	0.99	0.91
	Cd/Fe	-	1.00	1.10	1.04	0.99	1.09	1.00	0.96	1.19	1.23	0.91
	Pb/Fe	-	-	-	-	1.00	0.83	0.79	1.10	17.3	10.3	0.23
	Cu/Fe	-	0.95	0.97	1.01	1.00	1.00	1.00	-	1.16	1.18	-

The last three columns of Table 5 are for three streams at the St. Joe Minerals Corporation plant, where high grade (H.G.), intermediate (Int.), and prime western (P.W.) zinc are manufactured. It is apparent from the feed/product ratios for cadmium and lead for the three grades that the roasting process selectively removes Cd and Pb from the higher grade concentrates. Most likely, this is accomplished by running the roaster (at least in a first stage) at an oxygen deficit; as Figure 1 shows, the vapor pressures of PbS and CdS are appreciable at 1000 to 1200°C while that of ZnS is two orders of magnitude lower. In addition, the data from Table 5 would indicate that flue dusts from the high-grade and intermediate roaster, rich in Pb and Cd, would be added as feed to the prime western roaster.

The vapor pressure curves in Figure 1 demonstrate that the roasting process is conducted on the borderline of the temperature range where the oxides as well as the sulfides have appreciable vapor pressures. Most plants with fluid-bed roasters control the temperature to 900 to 1000°C by use of a water spray.

The data in Table 6 from the Canadian Electrolytic Zinc plant for 1969 provide the basis for a direct material balance (in tons) around two fluid-bed roasters, based upon independent analyses of the roaster feed and product. Within the analytical precision, these data verify the conclusions that there is little selective loss of cadmium in normal roasting (i.e., with an excess of oxygen and at temperatures controlled to less than 1000°C); and that the total losses in the flue gas are small compared to the quantity of cadmium in the concentrate.

The flue gas typically goes through a waste heat boiler and at least two stages of solids separation, a cyclone and an electrostatic precipitator, with the solids returned to the zinc process and with the gases (containing 9 to 13 per cent SO_2) used to manufacture sulfuric acid. Even after dust collection, the flue gas feed to the sulfuric acid plant may contain 0.097 per cent Zn and 0.00071 per cent Cd.(4) Analysis of

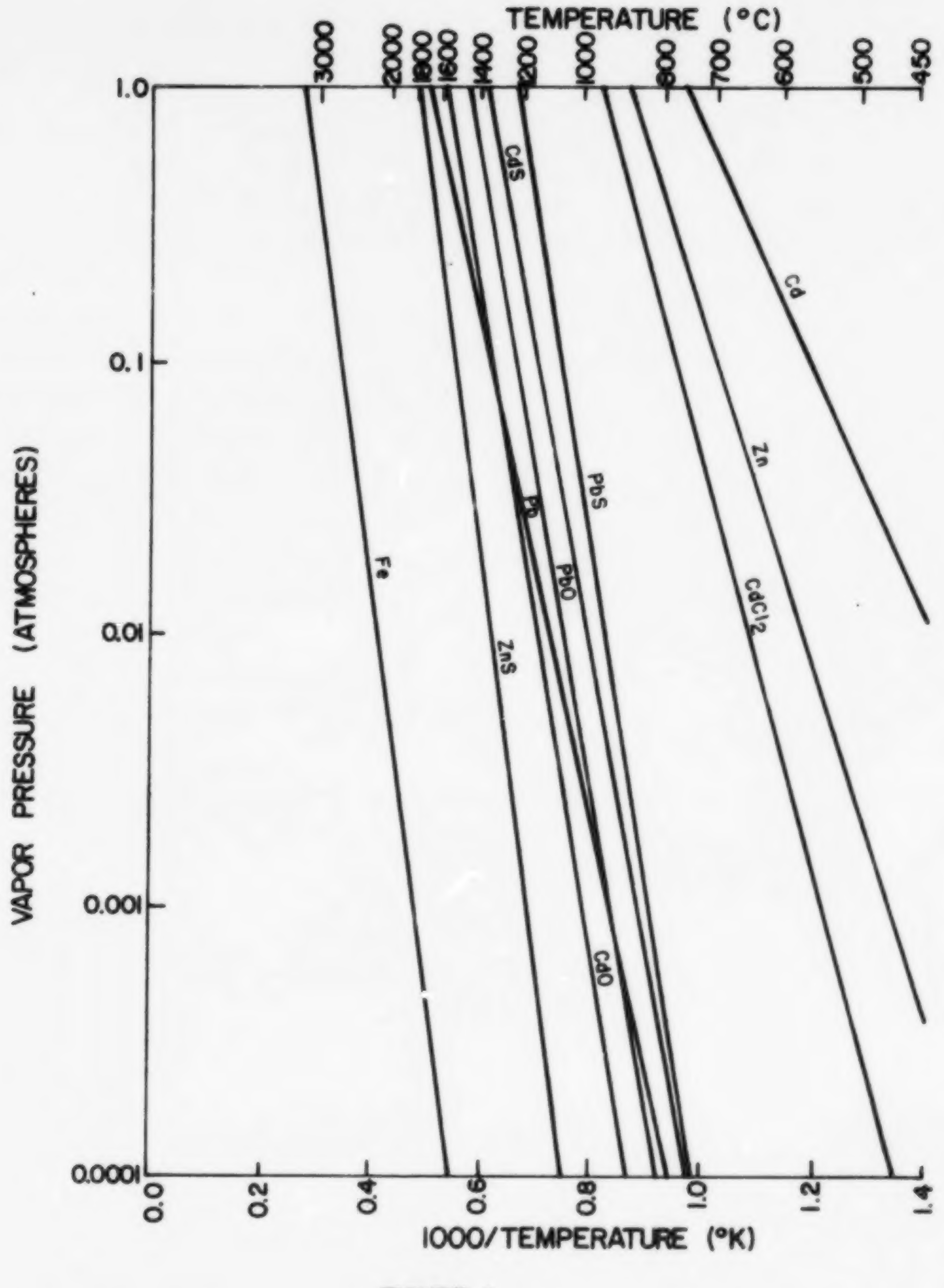

FIGURE 1
VAPOR PRESSURES OF METALS AND COMPOUNDS

TABLE 6

MATERIAL BALANCE AROUND ZINC ORE ROASTERS

SOURCE: AIME (5)

	CEZ	Allied
Ore Concentrate, Total	134,300	124,200
Zinc	71,500	65,300
Cadmium	360	140
Copper	830	470
Iron	13,600	12,900
Calcine, Total	116,800	106,300
Zinc	71,600	63,100
Cadmium	360	130
Copper	860	480
Iron	13,500	12,500

the byproduct sulfuric acid (76 per cent) from zinc smelters, as reported by Fulkerson,[(1)] shows a cadmium concentration of 20 to 60 ppm; any cadmium not collected as a solid oxide will be an impurity in the acid since CdO is soluble in sulfuric acid.

For a typical concentrate containing 54 per cent zinc and 31 per cent sulfur, the theoretical quantity of byproduct 76 per cent sulfuric acid will be 2.3 kkg per kkg of zinc produced. Even at a cadmium concentration of 60 ppm, the quantity of cadmium in the acid would be only 140 grams per metric ton of zinc produced. In comparison, the quantity of cadmium in the ore concentrate before roasting is equivalent to 5,000 grams per metric ton of zinc. Hence, the inferred loss of cadmium from roasting that winds up as an impurity in the sulfuric acid is of the order of 1 to 3 per cent of the total cadmium. This is consistent with the data of Table 6, which show that almost all of the cadmium is retained with the calcine.

The Fulkerson-Goeller study[(1)] revealed that the cadmium concentration of 76 per cent sulfuric acid from zinc smelters was 20 to 60 ppm. New data was obtained from industry sources in this study. One source said that to the best of their experience, the cadmium content of their byproduct sulfuric acid is in the range of 0.005 ppm. A second source said that a recent analysis of their sulfuric acid showed 0.06 ppm cadmium.

This large discrepancy may, of course, be attributed to erroneous data, to a change in the situation between the 1968 time frame and the present, or to a real discrepancy among producers. If the more recent data is in fact representative of the current situation, then of course no controls are required. If there are producers (other than those quoted above) who do have appreciable cadmium in byproduct sulfuric acid, then a regulation is in order, especially in light of the feasibility of such a regulation as demonstrated by the results of the quoted industry sources.

One such control option is to regulate the maximum cadmium content of sulfuric acid used by phosphate fertilizer manufacturers to about 2 ppm (such that the cadmium originating from phosphate rock would not be appreciably augmented). This control option would divert any high-cadmium sulfuric acid (if there in fact is any) to non-fertilizer applications. An alternate option is to directly regulate the maximum cadmium concentration of all byproduct sulfuric acid, ragardless of its intended use (with the exception, of course, of captive uses within the primary zinc/cadmium production cycle). This option prevents the dissipation of cadmium, as opposed to diversion, and places the burden at the source of the cadmium rather than at a single consuming industry.

After roasting, the next step in the pyrometallurgical route is sintering, in which coal or coke is mixed with the calcine, a binder may be added, nodules or briquettes are formed, and the green briquettes are fired with air at about 1200°C. The primary goal for sintering is to produce a feed for smelting in the form of a manageable briquette which has sufficient mechanical strength to avoid clogging and dusting in the retorts. In the sintering process, the volatile fractions of the coal are burned off, and any residual sulfur in the calcine (and in the coal) is oxidized.

"In addition to preparing a product with desirable physical characteristics for smelting, it was also discovered that certain volatile impurities could be removed and the resultant zinc produced therefrom was of higher quality than had been possible with previous practices."(5) This viewpoint of the industry (in 1953) truly expresses why sintering is the source of so much cadmium pollution - the loss of cadmium (and of lead) was intentional! At temperatures above 1200°C, the vapor pressures of lead and cadmium sulfides and oxides are sufficient to cause their volatization. To enhance this process, chlorides are added to the sintering machine to drive off volatile chlorides of lead and cadmium. At most plants, a significant fraction of the sinter is recycled through the sintering machine to further reduce the cadmium and lead content; at some plants, two full passes through sintering are practised.

Table 7 lists, for several sinter plants, the zinc, cadmium, and lead contents of the feed, product, and collected fume streams. For Eagle-Picher, four representative runs are listed, varying significantly from each other in terms of both feed composition and sinter product composition. The sinter machine operator has a great deal of flexibility in adjusting the feed mix (including the recycled sinter), the air flow, and the temperature.

A similar degree of flexibility is exhibited by the ASARCO Mexicana data; starting with the same calcine, two drastically different grades of sinter may be made. St. Joe Minerals performs the same type of classification, with material segregated at the roasting stage. New Jersey Zinc performs a two-stage sintering and coking operation, with coal added between stages. If is concluded, therefore, that aggregate industry data and data at any one particular plant may be widely misleading as to the effectiveness of removing cadmium and lead from the zinc in the sintering process. It is apparent from Table 7 that the cadmium/zinc ratio, nominally 0.5 per cent in the calcine, is reduced by sintering to no greater than 0.05 per cent and to as little as 0.003 per cent. Hence, the sintering process removes from 90 to 99 per cent of the cadmium in the calcine.

The dust is collected in a baghouse and is used (or sold) for the production of primary cadmium. ASARCO claims 99.5 to 99.9 per cent efficiency of collection.(5) The following chart, based upon 5 kg of Cd per kkg of Zn in the calcine, relates the Cd emitted to the atmosphere to the percentage removal of Cd from the calcine by sintering and to the collection efficiency of the baghouse:

TABLE 7

METAL CONTENT OF SINTER FEED AND PRODUCT

SOURCES: YOST,(4) AIME(5)

		Eagle-Picher				ASARCO		St. Joe				NJ Zinc	
		Run A	Run B	Run C	Run D	Run A	Run B	P.W.	Int.	H.G. Soft	H.G. Hard	Pass 1	Pass 2
Metals in Calcine (Feed), %	Zn	69.2	70.0	69.1	68.1	62.0		62.0	64.0	68.0		63	30
	Cd	0.58	0.40	0.61	0.13	0.63		0.40	0.25	0.22		0.24	0.033
	Pb	1.57	0.68	1.18	0.45	0.54		1.4	0.035	0.035		0.80	0.12
Metals in Sinter (Pdt), %	Zn	71.0	71.3	71.4	70.9	66.2	65.5	55.5	57.1	63.6	58.6	73	42
	Cd	0.037	0.032	0.013	0.002	0.02	0.002	0.017	0.015	0.012	0.006	0.077	0.011
	Pb	0.28	0.11	0.15	0.017	0.24	0.06	0.33	0.037	0.005	0.006	0.26	0.15
Metals in Collected Fume, %	Zn	45.1	33.1	41.6	43.8	13.0						33	63.7
	Cd	12.32	14.4	13.5	4.92	24.72						9.1	4.47
	Pb	20.1	25.4	22.0	14.2	21.9						15.6	3.18
Ratios in Sinter, %	Cd/Zn	0.052	0.045	0.018	0.003	0.03	0.003	0.031	0.036	0.019	0.010	0.106	0.026
	Pb/Zn	0.39	0.15	0.21	0.024	0.36	0.09	0.60	0.065	0.008	0.010	0.36	0.36

Values of Cadmium Emissions
kg Cd/kkg Zn

		Collection Efficiency of Baghouse		
		90	95	99
Cd Removal by Sintering, %	90	0.450	0.225	0.045
	95	0.475	0.238	0.048
	99	0.495	0.248	0.050

As these values show, the cadmium emissions are not greatly affected by the sintering process variations. However, they are directly affected by the baghouse efficiency.

If the domestic zinc production via sintering (i.e., non-electrolytic) is estimated at 417,000 kkg per year, then the total cadmium emitted by sintering in the U.S. would be about 100 kkg per year, based upon a 95 per cent collection efficiency for baghouses. Should 99 per cent efficiency be achieved by the entire sintering industry, the cadmium emissions would be 20 kkg per year from these sources.

Others have generated cadmium emission factors for the sintering operation. Yost(4) measured the metal content of stack emissions from the "coker" at the N.J. Zinc Palmerton, Pa. plant. This coking is a second-stage sintering step, after approximately 70 per cent of the cadmium and lead have already been removed from the calcine. At an attempt at making a material balance, up to 20 per cent of the cadmium input to the coker was still unaccounted for. The Yost emission factors are:

Cadmium,	0.96	kg/kkg Zinc in Feed
Lead,	0.51	kg/kkg Zinc in Feed
Zinc,	10.4	kg/kkg Zinc in Feed
Copper,	0.008	kg/kkg Zinc in Feed

These values must be regarded, however, as unique to the Palmerton plant for two reasons:

1. They apply only to the second stage of the sintering process as it is set up at this plant.

2. There apparently is no baghouse or other dust catcher in the exhaust train from this coker. The first stage sintering unit process does have precipitators, and the captured dust is the primary source for the cadmium plant. The only cadmium values apparently recovered from the coker, however, are those at the bottom of the exhaust stack.

Hence, it appears that the Yost data are not representative of the sintering process in the industry. As Yost points out, moreover, the metal emissions are very sensitive to temperature changes and to air flow changes. The variation in the data of Table 7 reinforce this conclusion.

The next major unit process in the pyrometallurgical route to zinc is retorting, to reduce the zinc oxide in the sinter to metallic zinc. The coal or coke in the sinter is the reducing agent. Three major variations of retorting are practised in the U.S.; horizontal retorts, vertical retorts, and the electrothermic process (see table of U.S. zinc plants). The reaction is carried out at about 1200°C to 1600°C, with metallic zinc vaporizing and subsequently collected in a condenser.

The oldest process is the horizontal retort process. It is conducted as a batch operation in batteries of small units, since the size of each retort is limited by heat transfer considerations (the retort is externally heated). The process is labor intensive (because of its batchwise nature), it is energy inefficient (about 5 per cent efficiency), it is inefficient in zinc recovery (about 10 per cent of the zinc remains in the retort residue), and it is very bad from an air pollution standpoint ("blue powder" or flue dust production is high). Impure zinc dust (90 - 92 per cent Zn) formed in the retort is used commercially as the zinc dust in hydrosulfite plants and as the pigment in zinc paints. This zinc dust varies widely in quality and price and is also derived from galvanizer's waste, from scrap diecastings, and from sweater billets.(18)

The charge to the horizontal retort is about 60 per cent sinter, 15 per cent coke and coal, about 22 per cent recycled blue powder, and minor amounts of dross, salt and fluorspar. The "stuffing" and loam are essentially sinter, with some coke breeze and clay. Typical metal contents around the horizontal retorts of ASARCO Mexicana are listed in Table 8.

The off-grade product (about 10 per cent of the furnace production) is refined either by liquation, redistillation or electrolysis. The table above shows that the little amount of cadmium remaining in the sinter (less than 10 per cent of the original cadmium in the ore concentrate and in the roaster calcine) is carried along with the zinc to the smelter product and to blue powder and dross.

Approximately 15 per cent of the zinc (and cadmium) in the furnace charge winds up as blue powder, which is largely zinc oxide formed in the condenser which does not coalesce in the liquid phase but is carried out as flue gas.(3) At a dust collection efficiency of 95 per cent, the emission to the atmosphere is 0.003 kg of cadmium per kkg of zinc produced. For a domestic horizontal-retort production level of zinc of 100,000 kkg per year, the emissions would amount to 0.3 kkg of cadmium per year from horizontal retorting.

The vertical retort is a continuous process which uses the carbon monoxide produced by the reaction for subsequent heating; it achieves a 10 per cent energy efficiency and achieves a higher zinc recovery with only about 3 per cent blue powder formation.(3,10) However, the intermittent charging of new briquettes to the top of the furnace results in the release of some metal vapors to the air collection system upstream of the zinc condenser (this is not the case in the closed system of the batch-process horizontal retort). The zinc is condensed in a splash condenser, and the off-gases are scrubbed; any solids are collected in a baghouse, and the cleaned gases (containing CO) are burned to provide heat for the reaction before being released to the atmosphere.

TABLE 8

METAL CONTENTS AROUND HORIZONTAL RETORTS

SOURCE: AIME[5]

	Zn, %	Cd, %	Pb, %	Cu, %	Fe, %	Cd/Zn, %
Furnace Charge	53.5	0.02	0.40	0.70	5.74	0.037
Dross	79.9	0.036	0.19	0.05	0.26	0.046
Blue Powder	68.4	0.028	0.78	0.48	3.48	0.041
Fine Residue	4.5	0.00	0.12	3.16	34.4	0
Slag Residue	0.5	0.00	0.50	3.72	32.3	0
Spelter (Product):						
Regular Prime Western	99+	0.035	0.60	0.0065	0.033	0.035
Off-Grade P.W.	99	0.007	1.07	0.0112	0.182	0.007
Refined Prime Western	99	0.007	1.03	0.0115	0.020	0.007
Dry Cell Alloy	99+	0.050	0.20	0.0004	0.015	0.050
Galvanizing Alloy	99+	0.018	0.15	0.0046	0.018	0.018

The metal content of the streams around the vertical retort at the N.J. Zinc plant at Palmerton, Pa., are:(4)

	% Zn	% Cd	% Pb	Cd/Zn, %
Coked Briquette Feed	42	0.011	0.15	0.026
Condensed Zinc Product	99.8	0.018	0.054	0.018
Retort Residue (bottoms)	7.2	0.0013	0.08	0.018
Retort Scrubber Solids	91	0.198	0.056	0.22
Retort Baghouse Solids	61	0.22	0.21	0.36

The above data indicate that fractionation of the cadmium does occur in the vertical retort condenser; the blue powder has a tenfold greater cadmium concentration than horizontal retort blue powder. If 3 per cent of the zinc charged winds up as entrained solids, the emission factor (at 95 per cent collection efficiency) is 0.006 kg of cadmium per kkg of zinc produced. For a domestic vertical-retort production level of zinc of 103,000 kkg per year, the emission would amount to 0.6 kkg of cadmium per year from vertical retorting.

The electrothermal process achieves 25 to 30 per cent energy efficiency by virtue of internal heating (as opposed to heat transfer through firebrick for the horizontal and vertical retorts). However, more expensive metallurgical coke must be used. The Cd/Zn ratio of the sinter feed (St. Joe Minerals)(5) is about 0.026 per cent, the same as for the Palmerton vertical retort; and except for the mode of energy transfer, the processes are basically the same. Hence, the same emission factor, 0.006 kg of cadmium per kkg of zinc produced, will be assumed. For a domestic production rate of 227,000 kkg per year of zinc, the cadmium emissions would be 1.4 kkg per year.

In the electrolytic route to zinc, the roasting of ore concentrate is the same as in the pyrometallurgical route (except that some more sulfate is tolerated in the calcine). Rather than submitting the calcine to a sintering step, the electrolytic plants process the impure zinc oxide using wet chemistry technology. This basic difference means, for practical purposes, that electrolytic plants do not have air pollution problems (downstream of roasting) that pervade the smelting plants.

The calcine in electrolytic plants is dissolved in sulfuric acid, leaving behind the insoluble lead, iron, arsenic, gold and silver. This sludge is processed or sold for the metal content. Two-stage leaching is generally practised to limit the amount of zinc co-precipitated. Recently, a significant process improvement has been instituted which circumvents the loss of zinc as the insoluble ferrite, $ZnO \cdot Fe_2O_3$ (the calcine contains 5-12 per cent iron); excess sulfuric acid, at 80 to 95°C, dissolves Fe_2O_3). Subsequent addition of a sodium, potassium or ammonium salt precipitates the iron as the crystalline jarosite, such as $NH_4Fe_3(SO_4)_2(OH)_6$, which is readily separated (as opposed to the hard-to-settle iron hydrate). The importance of this Jarosite process is that it boosts zinc recovery from the conventional 85 to 93 per cent to the 96 to 98 per cent plateau and also enhances the recovery of byproduct cadmium, copper, silver and lead. The effect is to make the electrolytic route much superior from an economics viewpoint to existing pyrometallurgical processes (where it was highly competitive before), so that virtually all zinc plants now under study, design or construction are electrolytic. Other improvements to the electrolytic process, also enhancing its economics, have included fluid-bed roasters, continuous leaching and purification, improved electrolysis, and improved materials handling such as anode stripping.(13,19)

The filtered solution from leaching is treated with zinc dust to precipitate cadmium, copper, nickel and cobalt; the resultant filter cake is an important source of primary cadmium. This purification of the zinc sulfate may be conducted in two steps: first, a deficit of zinc dust is added to precipitate copper (lowest in the electromotive series), which is filtered; the filtrate is then treated with more zinc dust to precipitate the other impurities. The second purification sludge typically contains 80 per cent cadmium and 5 per cent zinc. The effectiveness of this purification is such that the resultant solution contains less than 0.2 mg/l of cadmium; the electrolytic zinc product typically contains 0.00002 per cent cadmium.(3,5) The spent electrolyte which contains no cadmium is recycled as leach acid, so that there is no fundamental reason for significant waterborne wastes from this process. The leach residue and purification sludges are recovered for their metal values, so that land-destined pollution is avoided. It may be concluded that the electrolytic process for zinc recovery is essentially pollution-free, as compared to the pyrometallurgical processes.

Others have estimated cadmium emissions to the air from zinc smelters. EPA(20) developed a factor of 150 kg per kkg of cadmium in the ore concentrate, equivalent to 1.0 kg per kkg of zinc produced. EPA(21) lists the following emission factors for total particulates prior to any control measures (in kg per kkg of ore concentrate):

Roasting (multiple-hearth)	60
Sintering	40
Horizontal Retorts	4
Vertical Retorts	50
Electrolytic Process	1.5

Davis(11) published a factor of 142 kg of cadmium per kkg of cadmium in the ore concentrate; it apparently was the basis for the estimates of EPA(20) and of Fulkerson.(1)

The air emission factors developed in this analysis are:

Process	kg Cd emitted per kkg of Zn	kg Cd emitted per kkg of Cd charged
Roasting	~0	~0
Sintering	0.24	48
Horizontal Retort	0.003	0.6
Vertical or Electrothermal Retort	0.006	1.2
Electrolytic Process	~0	~0

These factors were based upon a realizable collection efficiency of 95 per cent for airborne solids. EPA's ratings for collection efficiency are 90 - 96 per cent for electrostatic precipitators and 97 - 99 per cent for baghouses.(21) Lower efficiencies may be attained by individual installations for any number of reasons, including:

1. The lack of dust collectors
2. Aerodynamic or particulate overloading
3. Fouling of precipitators
4. Torn fabric bags or leaks in ducts
5. Smaller particles than designed for.

However, this analysis assumes that currently-available technology of design, operation and maintenance of dust collectors will be implemented in the very near future if not yet practised.

Water pollution from the primary zinc (and cadmium) industry was studied intensively for the EPA Effluent Guidelines Division,(8) and the EPA Office of Solid Waste Management Programs is currently sponsoring a study of hazardous wastes from this industry. Earlier data, prior to the effluent guidelines study, gave cadmium concentrations in the effluents from two zinc smelters of 0.39 and 0.9 mg/l.(3) Data from the effluent guidelines study showed that the cadmium concentration in raw (untreated) wastes could be quite high and are highly variable; several measured raw waste concentrations were 0.6, 33, 0.05, 0.3, 0.15. 0.6, 0.16, 0.51, and 0.31 mg/l. Cadmium shows up in the raw wastes from the acid plant blowdowns and from the retort flue gas scrubber liquors.

Of particular significance was the cadmium concentration of 33 mg/l in the raw acid plant blowdown from the N.J. Zinc plant at Palmerton, Pennsylvania. This concentration translates into a cadmium loss in the blowdown of 134 grams per metric ton of zinc produced, or of approximately 3 per cent of the total cadmium in the zinc ore concentrate. This significant blowdown loss from the process, plus the cadmium lost in byproduct acid and cadmium lost in other raw aqueous wastes, offers at least a partial answer to the "unaccounted-for" losses of cadmium from this same plant, as reported by Yost.(4)

Treatment of the raw aqueous wastes, which contain cadmium as well as arsenic, mercury, selenium, and zinc, and suspended solids, is accomplished by liming and sedimentation. The effluent limitation guidelines are based upon an achievable cadmium concentration, after liming to pH of 10.5 and settling, of 0.5 mg/l, as shown in Figure 2. Upon application of the effluent flow for BPCTCA (1977) and BATEA (1983), the effluent guidelines for cadmium (30-day averages) are:

	BPCTCA	BATEA
Wastewater Flow, liters/kkg zinc	8,350	5,425
Cadmium in Effluent, kg/kkg zinc	0.004	0.0027

These effluent limitations guidelines apply to the entire primary zinc (including cadmium production) industry, regardless of process. Based upon a total production level for the industry of 490,000 metric tons of zinc per year (Table 3), the projected waterborne cadmium discharges from this industry would be 1.96 kkg (1977) and 1.32 kkg (1983).

Table 9 lists the cadmium discharges from six of the eight plants in the industry (as of the 1971/1972 time period). The total waterborne cadmium discharge, without the missing two plants, was about 7.5 metric tons per year. Hence, compliance with the effluent guidelines would reduce this cadmium discharge by a factor of at least 4 to 5. The effluent guideline development document(8) also estimated that the following additional costs (in 1971 dollars) would be associated with compliance by the entire industry:

	BPCTCA	BATEA	Total
Capital Costs	$1,515,000	$1,054,000	$2,569,000
Annual Costs	458,000	450,000	908,000

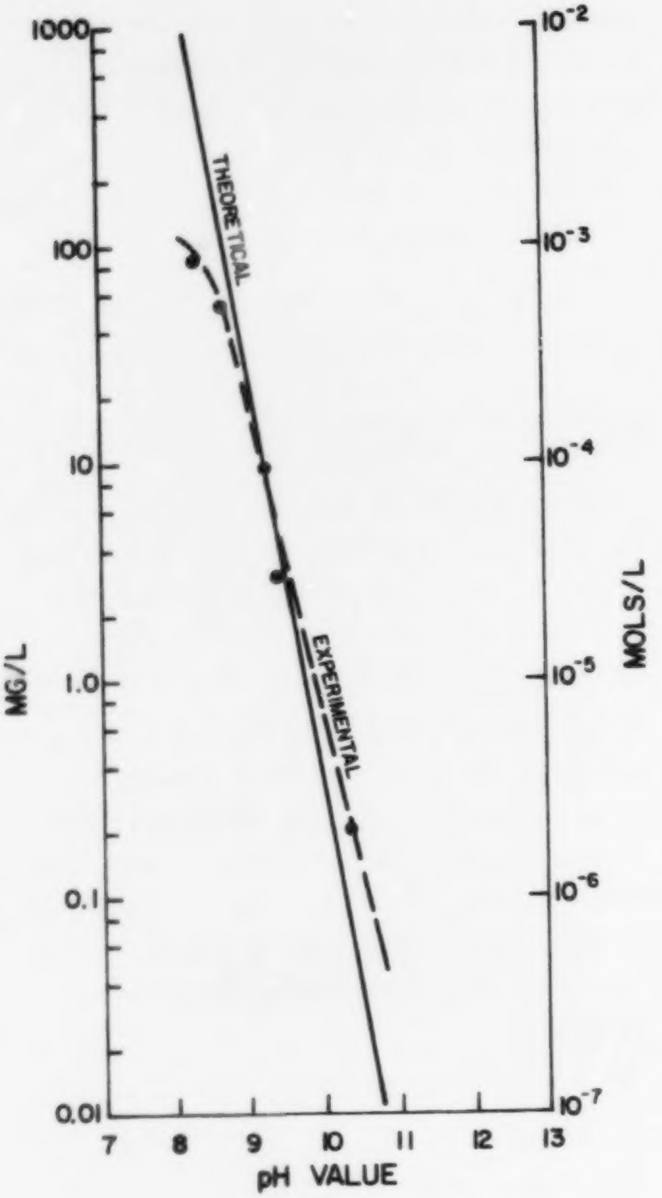

FIGURE 2
SOLUBILITY OF CADMIUM vs. pH
SOURCE: EPA(12)

TABLE 9

1971-72 CADMIUM WATERBORNE DISCHARGES FROM THE PRIMARY ZINC INDUSTRY

SOURCE: EPA[8]

Plant	Zinc Production kkg/yr	Cd Discharge, kg/kkg Zn	Cd Discharge, kkg/yr
ASARCO, Amarillo	42,300	0	0
ASARCO, Corpus Christi	98,000	2×10^{-4}	0.02
AMAX, E. St. Louis	64,100	-	-
Bunker Hill, Kellogg	110,300	0.044	4.85
N.J. Zinc, Palmerton	104,300	-	-
St. Joe, Monaca	226,800	0.01	2.27
National Zinc, Bartlesville	45,400	0.005	0.23
AMAX, Blackwell	72,800	0.002	0.15

These costs, of course, cannot be totally attributed to cadmium removal, since the same lime-and-settle treatment is effective in treatment of other heavy metals or suspended solids.

Trends in the Primary Zinc Industry

Two trends are evident in the production of primary zinc. First is the dramatic reduction in the domestic zinc production level over the last 20 years, and the second is the rapid phase-out of older pyrometallurgical smelters in favor of electrolytic plants. Both of these trends are, of course, directly beneficial in reducing the quantity of cadmium emitted to the air from U.S. zinc smelting operations. A side benefit of the worldwide switchover from retorting to electrolytic zinc is that much less cadmium is being dissipated to consumers as an impurity in zinc. Since the trend is towards less cadmium loss to the environment and less cadmium dissipated in the zinc products, the [illegible] is that more recoverable cadmium is becoming available for the primary cadmium industry. Compared to a ratio of cadmium to zinc in ore of 0.5 per cent, the following ratios of primary cadmium production to primary zinc production indicate that the maximum ratio is being approached:(1)

Years	Ratio of Cadmium Production to Zinc Production
1901-1910	0.002%
1910-1920	0.009%
1920-1930	0.056%
1930-1940	0.17%
1940-1950	0.25%
1950-1960	0.27%
1960-1968	0.33%

The regulatory alternative proposed is that extremely stringent air pollution controls be imposed. This would have the effect of encouraging those older smelters still with air pollution problems to close in favor of newer electrolytic plants rather than absorb the high costs for very efficient particulate control. For example, the imposition of a 99 per cent collection efficiency standard would reduce the estimated cadmium emissions from sintering to 0.05 kg per kkg of zinc. A mechanism for setting such a standard for a particular plant is to impose a limitation as a small percentage of the cadmium originally in the ore concentrate; in this way, there is no need for determining a complete cadmium material balance around every unit process for enforcement purposes.

Such an emission regulation should be accompanied by regulating the maximum percentage of cadmium in the zinc produced, to prevent the smelter from complying with the emission standard by allowing cadmium to be dissipated in zinc.

Other accompanying regulations would effectively prohibit the unsecured land disposal of cadmium-bearing flue dusts and sludges. The water-borne waste limitations already exist (or are already formally proposed).

SECTION V

CADMIUM ELECTROPLATING

The data in Table 10 show that the domestic consumption of cadmium, as a percentage of all cadmium consumed, has remained at approximately the same level since 1963.

All of the cadmium used in "transportation" is for electroplating. In 1968, of the total of 950 kkg consumed in transportation, 590 kkg was used in motor vehicles and 360 kkg in aircraft and boats. At a production level of motor vehicles of about 12 million per year, each vehicle would contain about 50 grams of cadmium as electroplate (this number will be used as the basis for estimating the cadmium flow in ferrous scrap at steel plants). The parts plated are small springs, screws, other fasteners, electrical contacts, and other small components. The use of cadmium-plated hardware in boats is due to the superior performance of this coating in a marine environment. Cadmium-plated fasteners are used extensively in aircraft; for example, of the 3.3 million fasteners in each Boeing 747, 2.8 million do not require a coating (aluminum alloys and titanium alloys), but 500,000 are steel alloys which are coated, many with cadmium.

The non-transportation end items which are cadmium-plated include nuts, bolts, washers, springs, nails, rivets, radio and television parts, malleable fittings, electrical parts, wire screen, appliance hardware, tools, and even casket hardware.

The thickness of most cadmium electroplate is about 0.0007 cm, equivalent to a deposition of about 60 grams per square meter. For an annual consumption of 3,000 kkg of cadmium for all electroplating, the area plated is approximately 50 million square meters.

The electroplating industry is characterized by the great diversity among the approximately 20,000 separate shops. There are captive shops,

TABLE 10

CADMIUM CONSUMED IN ELECTROPLATING

SOURCES: PAGE,[2] BUREAU OF MINES[15]

Year	Cadmium Consumed for Electroplating, kkg/yr			Per Cent of all Consumption
	Transportation	Other Electroplating	Total	
1963	500	2,220	2,720	54
1964	410	1,450	1,860	47
1965	630	1,770	2,400	52
1966	730	2,950	3,680	56
1967	860	2,220	3,080	61
1968	950	2,680	3,630	63
1969	1,040	2,950	3,990	63
1970	770	1,270	2,040	49
1971	950	1,450	2,400	48
1972	1,130	1,680	2,810	50

and there are job shops which do electroplating under contract for manufacturers. Half of the shops have less than 15 employees per shift, while 90 per cent have less than 50 employees per shift. Conversely, 10 per cent of the shops account for one-third of the total industry capacity; and only 10 per cent of the value added for electroplating is attributed to non-captive job shops. Both the plant size and the cadmium percentage vary widely: cadmium plating is more than 50 per cent of the workload in some plants and is a negligible part in other plants.

Some insight may be gained by an analysis of a representative job plating shop.(22) In one month, this shop plated a total of 24,260 square meters, broken down as follows (as per cent of the total):

Plating Metal	Automatic Rack	Automatic Barrel	Miscellaneous Barrel	Total
Copper, Nickel, Chrome	36.4	2.4	2.1	40.9
Zinc	26.1	20.3	0.3	46.7
Cadmium	2.9	0	9.5	12.4
TOTAL	65.4	22.7	11.9	100.0

Typically, this shop combines the zinc and cadmium plating in the same department; both use cyanide baths, the same plating technology, and (except for the anode cost) have the same plating costs.(23)

Of interest is the breakdown, by metal, between rack (large parts) and barrel (small parts) plating. The copper-nickel-chrome plating is 90 per cent rack plating, the zinc plating is 60 per cent rack plating, while the cadmium plating is only 20 per cent rack plating. Hence, at least for this shop, cadmium plating is predominantly applied to the smaller parts. Further, this shop is representative in that only a minor fraction of its total plating is with cadmium, and the volume of zinc plating is significantly higher than the volume of cadmium plating.

Each 36 cm x 91 cm barrel may typically contain 70 kg of small steel parts with a total surface area of 4.5 square meters. Hence, a representative small parts ratio is 65 square meters per metric ton. If 60 grams of cadmium are applied per square meter, an equivalent ratio would be 3.9 kg cadmium per metric ton of plated parts. Of course, larger parts (rack-plated) would have a much lower cadmium-to-steel ratio.

The raw waterborne metal wastes from electroplating arise primarily from dragout of plating solution, by the plated parts, from the plating baths to the rinse tanks. Other important sources of raw aqueous wastes are discarded plating baths, spills and overflows from plating baths, equipment cleanup wastes, and sludges which accumulate in plating baths. Many plating shops treat wastewaters for cyanide by oxidation with chlorine or with sodium hypochlorite, but prior to 1972, few plating shops treated wastewaters for cadmium removal.(4) Some extreme cases of cadmium pollution from electroplating have been noted in the literature,(2) such as a 3.2 mg/l cadmium concentration in ground water in Long Island, and a cadmium concentration of 300 mg/l in an effluent in Southern California (with resultant soil concentrations of up to 30 ppm cadmium).

The standard treatment for cadmium (and other metals) in electroplating wastewater is the precipitation as the hydroxide or carbonate (using lime, caustic soda, or soda ash) at pH 9.2 to 10.9,(1,22,24) with subsequent clarification or filtration. Efforts to reduce the raw wastes are also being implemented, such as the countercurrent flow of rinse water, and "housekeeping" improvements in the process area. Some approaches, such as segregation of cadmium wastes from other metal wastes with subsequent recovery via ion exchange and the use of caustic soda/soda ash solutions as a first rinse after the plating bath, have been implemented in a few plants.(22,24)

The raw waste load varies substantially in the electroplating industry. The raw waste from zinc plating (using similar equipment and technology to cadmium plating) may be estimated from a zinc concentration prior to treatment of 32 mg/l and from a water use of 0.65 liters per amp-hour at one plant.(24) Using a typical current efficiency of 60 per cent for zinc plating from a cyanide bath, the calculated raw waste load is 28 kg per metric ton plated (2.8 per cent of the zinc plated).

A correlation of seven electroplating shops revealed that the 1972 state-of-the-art of wastewater treatment could be expressed (regardless of metal plated) as a treated discharge of 3.5 kg metal per metric ton plated (0.35 per cent of the plated metal).(24) Hence, comparison of this factor with the above raw waste factor indicates that average treatment is close to 90 per cent effective in the 1972 time frame. In addition, the use of these two factors applied to 3,000 kkg per year of cadmium plated means that the cadmium discharged in the effluent is 10.5 kkg per year and that the cadmium in the waste treatment sludge is 73.5 kkg per year.

The proposed 1977 effluent guidelines(24) for zinc, copper, nickel, and chromium electroplating are 80 mg of metal per square meter plated (per plating operation). Assuming that since cadmium plating is virtually the same as zinc plating, the 80 mg/m^2 limitation would be equivalent to 1.33 kg cadmium per metric ton of plated cadmium (0.133 per cent). Using the above raw waste load factor of 28 kg per kkg plated, an implied treatment efficiency is 95 per cent. Applying these 1977 projections to 3,000 kkg per year of cadmium plated means that the cadmium discharged in the effluent would be 4.0 kkg per year and that the cadmium in the waste treatment sludge would be 80 kkg per year.

The proposed 1983 effluent guidelines for electroplating (again extrapolated to cadmium) is zero discharge of cadmium. The technology basis for this limitation includes in-process changes to reduce the raw waste load (i.e., countercurrent rinses) plus total recycle of process water after chemical treatment, plus recovery of the metals by evaporation, ion-exchange, or reverse osmosis. This technology implies that neither waterborne nor land-destined wastes would occur from electroplating in 1983.

In the case of cadmium, the separately-proposed toxic substances effluent limitations(10) may hasten the zero-discharge implementation.

The capital investment required to achieve the 1977 BPCTCA effluent limitation was estimated to be $150,000 per 100 square meters per hour of plating capacity; and the additional capital investment for achieving the 1983 BATEC zero discharge effluent limitation was estimated to be $100,000 to $200,000 per 100 square meters per hour.(24) On the basis of a total cadmium plating industry capacity of 25,000 square meters per hour (50 million square meters per year and 2,000 operating hours per year), the investment costs for the industry would be $37.5 million for BPCTCA plus $25 to $50 million for BATEC. For comparison, the value added from cadmium plating is approximately $3.20 per square meter or $160 million per year. It was estimated that the incremental cost of pollution control would be less than 5 per cent of the plating cost for BPCTCA and would be approximately 10 per cent for BATEC.(24)

In addition to the wastewater treatment costs, the residual sludges must be either processed for cadmium recovery or disposed of in an environmentally adequate manner. The disposal costs are estimated to be $400 per kkg (dry solids basis) for chemical fixation and landfill, or $600 per kkg (dry solids basis) for secured landfill of the sludge.(25,38) The quantity of dry solids as $Cd(OH)_2$ in residual sludges implied by the 1977 guidelines is 104 kkg per year for the entire cadmium plating industry. Hence, the disposal costs would be about $50,000. In contrast, the value of the cadmium in this sludge, at $8.80 per kg, amounts to $720,000 per year as an incentive for recovery.

The costs for electroplating, exclusive of the metal costs, are in the range of $2.70 per square meter. For cadmium plating, about 60 grams are used per square meter, with a cost (at $8.80 per kg) of about $0.55 per square meter plated, bringing the total cost to $3.25 per square meter. In comparison, the cost of zinc (at $0.50 per kg and at 100 grams per square meter) is about $0.05 per square meter plated, for a total plating cost of $2.75 per square meter.

Pollution control requirements imposed by local, state, and federal standards, have increased the costs for electroplating. Most platers have already adopted some type of waste treatment; the initial emphasis has been on cyanide and on hexavalent chromium, but recent attention has been on other heavy metals including cadmium. The higher toxicity of cadmium relative to zinc has brought about, and will continue to generate, much more restrictive effluent standards for cadmium. This is expected to cause the cost of cadmium plating to rise faster (compared to zinc electroplating). There is a movement away from cadmium in electroplating because of pollution control requirements, because the cost of cadmium is a larger percentage of the total electroplating cost than it is for zinc, and because the price of cadmium has increased and its availability has been curtailed.

Auto manufacturers have begun to use chromate and oil corrosion protection in place of cadmium plating for some applications, and others have begun to use zinc plating in place of cadmium plating for corrosion protection and tin for electrical parts. However, it seems probable that since cadmium has always been more expensive than its potential substitutes, substitutes have been already made where possible. Much of cadmium plating is for high-quality parts, or critical parts, or in applications (military and aircraft) where firm specifications impede changes and substitutions. Cadmium plating is already (and always has been) a very small part of the metals finishing industry. Hence, since cadmium plating is an expensive specialty, and, as such, is demanded where substitutes are not totally equivalent, the price of cadmium would have to be significantly higher (perhaps $20 per kg) before price would have a substantial effect on demand.

The control alternatives include, of course, the effluent limitation guidelines and the toxic substances guidelines discussed earlier. Since wastewater treatment would result in an inter-media transfer of cadmium from water to land-destined waste, an effective control strategy must include regulations for environmentally-adequate land disposal of residuals as well as waterborne waste regulations.

Many electroplating shops are in highly-industrialized cities, and have historically discharged into municipal sewer systems. Of 53 electroplating facilities evaluated in the development of effluent guidelines, 25 discharged into municipal sewer systems rather than directly to streams.(24) New York City alone has 250 electroplating firms discharging a total of 30 kg of cadmium per day into the city's sewers.(27)

Four kinds of undesirable effects occur as a result of the discharge of cadmium into municipal wastewater systems:

1. In those areas with combined sewers and with frequent overflows, a portion of the cadmium is directly released to the receiving waters.
2. Much of the cadmium will not be removed by municipal sewage treatment plants, and will be released to the receiving waters.
3. Cadmium in excessive quantities may poison biological treatment operations, such as secondary wastewater treatment or anerobic sludge digestion.
4. Some of the cadmium will be adsorbed into the sludge. If the sludge is incinerated, the volatile cadmium oxide would not likely remain as part of the ash. Scrubbing systems would return the cadmium to the wastewater plant, eventually leading to discharge in the effluent. The cadmium oxide not scrubbed out of the flue gas would be directly released to the environment. If the sludge is landfilled, it is likely that some would be leached, polluting surface and ground waters. If the sludge is applied to agricultural land, the cadmium uptake by plants would lead it into the food chain.

For the above reasons, it is imperative that effluent limitation guidelines also include pretreatment standards which effectively prohibit the discharge of cadmium into municipal sewer systems.

Another control strategy is a full or partial ban on cadmium electroplating. Besides the direct elimination of cadmium pollution from the electroplating industry, the limitation or cessation of cadmium electroplating would result in a major reduction in the cadmium emitted by the steel industry in their processing of scrap. Moreover, a ban on cadmium electroplating would halve the cadmium use (and dissipation) and reduce imports to zero. It is implied, of course, that such an option would be coupled with control measures restricting cadmium emissions at zinc smelters.

CADMIUM IN PLASTICS

Cadmium compounds are used extensively for formulating plastics molding compounds in two ways: as a heat stabilizer and as a pigment. Much of the plastic products containing cadmium wind up in the municipal solid waste stream, and the portion of this stream that is incinerated releases cadmium to the environment via the inefficiency of incinerator flue gas scrubbing systems, the wet scrubber effluents, and the landfilling of incineration residues.

Cadmium Pigments - Use Pattern

Table 11 lists the quantity of cadmium used in manufacturing pigments for all uses, and the quantity of cadmium colorants used in the plastics industry. The actual cadmium content in colorants depends upon the particular pigment (cadmium sulfide or cadmium sulfoselenide) and whether the colorant is a pure toner or a lithopone. Of the total quantity of cadmium colorants consumed for all uses (2,500 metric tons per year), approximately 700 kkg is in the form of C.P. toners (i.e., pure compounds) with an average cadmium content of 70 per cent; and 1,800 kkg is in the form of lithopones with an average cadmium content of 25 per cent. Hence, the overall percentage of cadmium in all colorants is about 38 per cent. This infers that approximately 75 per cent of all cadmium pigments are consumed in plastics; an independent industry estimate was 90 per cent.(30)

The pigments are also used in interior water-base paints, durable enamels, coated fabrics, textiles, rubber, printing inks, artists' colors, glass, and ceramic glazes.

The data in Table 12 show the cadmium colorant consumption in plastics in relation to other colorants used in plastics. These data show that white and black colorants constitute 86 per cent of the total consumption in plastics; and that cadmium colorants account for only 2 per cent of all

TABLE 11

CONSUMPTION OF CADMIUM PIGMENTS

SOURCES: BUREAU OF MINES,(28) MODERN PLASTICS(29)

	Cd Content in Pigments for All Uses, kkg of Cadmium per Year	Cd Colorants for Plastics, kkg of Colorants per yr
1968	1,110	2,000
1969	1,100	2,140
1970	970	2,090
1971	1,010	2,180
1972	1,230	2,300
1973		2,630
1974		2,750

TABLE 12

PLASTICS COLORANT CONSUMPTION
SOURCE: MODERN PLASTICS(29)

	Consumption in Plastics, kkg/yr			
	1971	1972	1973	1974
Titanium Dioxide	79,100	86,000	95,000	94,000
Carbon Black	20,500	23,500	27,000	27,000
Cadmium Colorants	2,180	2,300	2,630	2,750
Other Inorganics*	8,140	9,250	10,560	10,200
Organics (incl. Dyes)	5,980	6,430	7,240	7,090
Grand Total	115,800	127,500	142,400	141,000
Total (Other than white or black)	16,300	17,980	20,430	20,040

*Includes chrome yellows, molybdate oranges and iron oxides colorants and 13 per cent of the non-black-or-white colorants. Much of this distribution is a result of the wide range in colorant prices, shown in Table 13. The very high price for the cadmium reds and maroons is the result of the high price of selenium.

The plastics molder will generally use the cadmium lithopone over the C.P. toners, since they provide more tinctorial power per dollar. However, the C.P. toners are used where physical properties of the plastic are critical since less is used. In a great many cases the cadmium colorants are used together with titanium dioxide to give a range of color shades.

Colorants are generally used in the range of 1 to 4 per cent of the resin (depending to a large extent upon the tinctorial power of the colorant), with an average of about 1.25 per cent. Hence, the colorant costs per kilogram of resin fall into these general ranges:

Iron Oxides, Carbon Black, TiO_2	0.4 - 1.1 cents/kg
Chrome Yellows, Iron Blues, Molybdate Orange	1.8 - 2.8 cents/kg
Organics	6 - 20 cents/kg
Cadmium Lithopones	7 - 16 cents/kg
CP Cadmiums	16 - 36 cents/kg

A perspective is gained by these representative (1973) resin price levels;(31) the cost of the organics and cadmium colorants are a major portion of the materials cost:

Low-density polyethylene, Polyvinyl chloride	$0.27/kg
High-density polyethylene, Polystyrene	0.31/kg
Polypropylene	0.37/kg
Polyvinyl Acetate, Melamine/Urea	0.44/kg
Phenolics	0.48/kg
ABS/SAN	0.55/kg
Acrylics	0.80/kg
Epoxies	1.30/kg
Nylon	1.50/kg

TABLE 13

RECENT PRICES OF PLASTICS COLORANTS
SOURCES: MODERN PLASTICS,(29) DCMA(30)

Colorant	Price, $/kg (June 1974)
Titanium Dioxide	$ 0.88
Carbon Black	0.30
Iron Oxides (Yellow & Red)	0.45
Iron Blues	2.20
Chrome Yellows	1.45
Molybdate Oranges	1.85
Cadmium Lithopones:	
Yellows	5.90
Oranges	7.90
Reds	9.80
Maroons	12.70
CP Cadmiums:	
Yellows	13.30
Oranges	19.00
Reds	24.00
Maroons	28.70
Organics	5.00-15.00

The data of Table 14 showing the 1974 colorant consumption by resin type indicates that colorants are widely disseminated among resin types (and so among end products). However, the high price of cadmium colorants discourages their use in cheap, disposable end items; these colorants are more generally used for durable, high-quality end items.

Table 15 lists the yellow, orange, red, and maroon colorants (the colors of cadmium pigments) widely used for each type of resin. It is apparant that cadmium pigments are widely used in all types of resins and so are widely disseminated in plastic end products. It may therefore be concluded that the distribution of the 500 metric tons per year of elemental cadmium in plastics (as colorants) is homogeneous with respect to ultimate incineration of plastic end-items.

Table 15 also shows that the list of alternate colorants is fairly extensive for many of the resins, particularly for low density polyethylene and polyvinylchloride. On the other hand, few if any substitutes are available for ABS, acetal, nylon, polycarbonate, fluoroplastics, diallyl phthalate, and silicones. Of these resins, several have critically high heats of processing which limit the choice of colorant; among these are the fluorocarbons, the nylons, and polycarbonates. Silicones, while not processed at high temperatures, are used in service at high temperatures. Others of these resins exhibit chemical reactivity which limits colorant selection; included are the acetals, acrylics, polyesters, epoxies, and urethanes. It should be noted that where cadmium colorants have few alternates, the resins are also relatively high-priced, so that cadmium colorants may be justified.

It is important to emphasize that cadmium pigments have properties which cannot be matched by any potential substitute (for the same color). The cadmium pigments are totally non-bleeding (not soluble in the resin) and are alkali-resistant; these properties make them especially suitable for plastic automobile interiors. Cadmium pigments yield very high opacity (for applications where this is important), and extremely bright colors (where identification, visibility, or safety is involved). The high-temperature properties of cadmium pigments, as mentioned previously,

TABLE 14

COLORANT CONSUMPTION BY RESIN TYPE

SOURCE: MODERN PLASTICS (29)

Resin	Total Resin Million kkg	Resin Containing Colorants, Million kkg	Colorants Consumed Thousand kkg	Resin Colored, % of Total	Colorant, % of Total Resin
Low-Density PE	2.769	1.261	22.7	46	0.82
High-Density PE	1.275	1.020	10.9	80	0.85
Polyvinyl chloride*	2.180	1.994	33.6	91	1.54
Polystyrene*	2.328	1.619	28.4	69	1.22
Polypropylene	1.061	0.817	10.1	77	0.95
All Resins	13.350	—	141.0	—	1.06

*Including copolymers

TABLE 15

YELLOW, ORANGE, RED AND MAROON COLORANTS WIDELY USED WITH VARIOUS RESINS

SOURCE: MODERN PLASTICS ENCYCLOPEDIA(32)

Colorant	ABS	Acetal	Acrylics	Cellulosics	Nylons	LD Polyethylene	HD Polyethylene	Polypropylene	Polycarbonate	Fluoroplastics	Polystyrene-GP	Polystyrene-IR	Vinyls-Flexible	Vinyls-Rigid	Amino Resins	Diallyl phthalate	Phenol Formaldehyde	Polyester, Alkyd	Silicones	Epoxy	Polyurethane
Inorganics -																					
Cadmium Sulfide	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
Cadmium Sulfoselenide	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Iron Oxide Yellow, Red	X	X		X		X	X	X			X	X	X	X			X	X	X	X	X
Chrome Yellow, Orange													X	X	X	X	X	X		X	X
Molybdate Orange													X	X	X	X	X	X		X	X
Ultramarine Red	X			X	X	X	X	X	X		X	X			X	X	X	X	X	X	X
Organics -																					
Quinacridone Red						X	X	X					X	X							
Anthrapyrimidine Yel.		X				X							X	X					X		X
B.O.N. Red						X	X	X					X								
Thioindigo Red						X							X	X							
Red Lake R Red						X					X										
Pyrazolone Red													X								
Anthraquinone Red			X		X	X	X				X	X	X	X	X		X	X		X	X
Isoindolinone Red			X	X		X							X	X	X			X		X	X
Perylene Red			X	X		X							X	X				X		X	X
Anthraquinone Yellow				X		X					X		X	X							
Benzidene Yellow, HR							X						X	X							
Hansa Yellow															X		X				
Dis-Azo Yello, Or., Red			X	X		X	X	X			X	X	X	X			X	X		X	X
Pyranthrone Orange													X	X			X				
GR Perinone Orange						X	X	X					X	X			X				
Isoindolinone Or., Yel.				X		X	X	X					X	X	X		X	X		X	
Flavanthrone Yellow						X							X	X							

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are quite important in certain resin systems. It should be mentioned that the entire heat history of a pigmented resin is critical; even though some organic pigment may survive a once-through molding process, it may not be suitable for scrap rework (and so the molding economics would suffer).

Potential substitutes for cadmium colorants, such as the chrome colors, the lead colors, and the polynuclear aromatics, pose their own toxicity problems which must, of course, be taken into account in formulating control regulations.

The difficulties in finding direct substitutes for cadmium colorants are, to a large measure, dictated by aesthetics. At one extreme, either white (titanium dioxide) or black (carbon black) might be used for all resin systems at low prices and with high performance. Realistically, however, the aesthetics of color (other than white or black) are part of our commercial world, and price differentials are being justified for this purpose.

In summary, then, it appears that the high price of cadmium pigments, as compared to others, has already made the choice of cadmium pigments highly selective (i.e., where no cheaper substitute will suffice to meet the coloring requirements of the resin system and of the end-item application).

In light of the above discussion, a potential control strategy would be a partial ban on the use of cadmium colorants in plastics. Exemptions might be based upon:

1. The necessity for the specific color and color quality in the end item.
2. The necessity for the particular resin system for the end item (i.e., would an alternate resin-colorant combination satisfy product requirements).
3. The demonstration that the end item would not quickly or largely enter the municipal solid waste stream.

4. The demonstration that the quantity of such end items is not large.
5. The demonstration that substitutions create pollution problems equal in magnitude and severity.

Manufacture of Cadmium Pigments

Cadmium pigments (red, orange, yellow and cadmium lithopone) are all generally produced by the method described on Figure 3. The amounts and types of reactants are varied to produce the desired color. Cadmium red is essentially cadmium selenide; the yellow is a mixed cadmium-zinc sulfide, and the orange is somewhere in between. Cadmium lithopone is a mixed barium sulfate-cadmium sulfide co-precipitate made by using barium sulfide to precipitate the product instead of sodium sulfide used for the other cadmium colors. The quantities noted on Figure 3 are a material balance referenced to 1000 mass units of pigment produced.

The losses to the atmosphere from the calcination step were estimated by Davis to be 8 kg per kkg processed (0.8 per cent).(11) The Davis estimate is based upon efficient dust collection equipment (i.e., baghouses) which return much of the calcination dust to the process.

Waterborne wastes arise from the filtration and washing operation, both as dissolved cadmium salts in the spent mother liquor and washings, and as suspended solids. The raw waste load (before treatment) was determined for similar inorganic pigment processes (chrome pigments, lead pigments and zinc pigments) to be in the range of 10 to 20 kg per kkg product.(33) Neutralization and precipitation with lime, with subsequent clarification in settling ponds, was found to remove 90 to 95 per cent of the heavy metals, resulting in a waterborne discharge of about 0.3 kg of metal per kkg of product pigment. The estimated capital cost for this treatment is about $55 per kkg of annual production, and the estimated total costs (capital recovery and operating cost) are about $20 per kkg

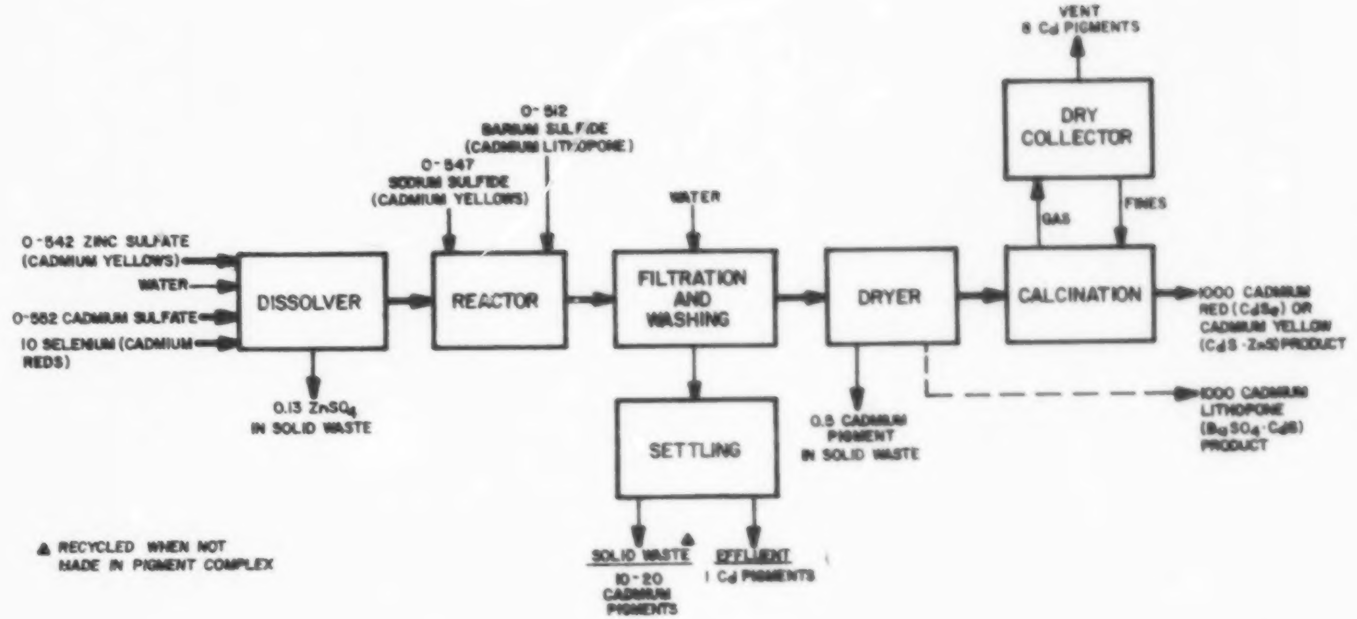
0-542 ZINC SULFATE (CADMIUM YELLOWS)
WATER
0-582 CADMIUM SULFATE
10 SELENIUM (CADMIUM REDS)
DISSOLVER
0.13 ZnSO4 IN SOLID WASTE
0-547 SODIUM SULFIDE (CADMIUM YELLOWS)
0-512 BARIUM SULFIDE (CADMIUM LITHOPONE)
REACTOR
WATER
FILTRATION AND WASHING
SETTLING
SOLID WASTE ▲
10-20 CADMIUM PIGMENTS
EFFLUENT
1 Cd PIGMENTS
DRYER
0.8 CADMIUM PIGMENT IN SOLID WASTE
VENT
8 Cd PIGMENTS
DRY COLLECTOR
GAS
FINES
CALCINATION
1000 CADMIUM RED (CdSe) OR CADMIUM YELLOW (CdS·ZnS) PRODUCT
1000 CADMIUM LITHOPONE (BaSO4·CdS) PRODUCT
▲ RECYCLED WHEN NOT MADE IN PIGMENT COMPLEX

FIGURE 3
CADMIUM PIGMENT MANUFACTURE

produced. Further, it was found that the majority of the inorganic pigments industry already meets this level of treatment. An independent EPA study(34) gave results consistent with the above data.

Technology for treating zinc yellow waterborne wastes, first by ion exchange and then with soda ash (to precipitate the highly insoluble zinc carbonate) resulted in a further reduction in the effluent to approximately 0.02 kg of metal per kkg of product. This technology seems directly transferable to cadmium pigments.

In plants producing only cadmium colors, the solid waste generated by wastewater treatment can be (and is) recycled back to the process. This cannot be done at large chrome pigment complexes where cadmium colors are made and a single large treatment facility exists for the entire complex. The other solid waste stream destined for land disposal contains slightly contaminated dry chemical bags and in-plant product transfer containers (non-metallic).

The quantity of the cadmium pigments in the land-destined waste stream was estimated as 10 to 20 kg per kkg of product as wastewater treatment residuals plus 0.5 kg per kkg of product as residuals in discarded containers.(25) In addition, this waste stream contains, on a dry basis, approximately 200 kg/kkg product of non-hazardous materials such as filter aids, calcium sulfate (from lime treatment of sulfates), water treatment residuals, and discarded containers.

At present, although the pigments industry has spent large sums of money for wastewater treatment, the land-destined waste stream is not disposed of in an environmentally-acceptable manner. Land dumping, disposal in general-purpose landfills, pond storage, and even disposal into municipal sewer systems are prevalent. Leaching of the cadmium to contaminate both surface and ground water is a distinct probability. A small fraction of the plants, expected to increase drastically by 1977, practice waste disposal in a secured landfill (landfill integrity with leachate control and monitoring of surface and ground water). It is also estimated that 25 per cent of the industry's cadmium residuals may be recovered instead of disposed by 1983; and that chemical fixation of the non-recoverable wastes (now in the pilot-plant stage) would become operational.

Cost estimates for land-dumping or unsecured landfill disposal were $1.90 per kkg of product pigment; costs for secured landfilling or chemical fixation are estimated as $7.50 per kkg of product pigment.

The quantity of cadmium pigments produced in 1974 is estimated as 2,500 kkg (of which 1,100 kkg is elemental cadmium). Using the factors developed above, the annual emission of cadmium in effluent water is 0.75 kkg. The quantity of cadmium pigments currently disposed of to land in an inadequate manner is 37.5 kkg per year, containing 16.5 kkg per year of elemental cadmium. Hence, the total estimated loss of elemental cadmium to the environment is 26 kkg per year from the manufacture of cadmium pigments.

Based upon the implementation of EPA regulations for the land disposal of hazardous wastes and for waterborne wastes, only the 9 kkg per year of airborne cadmium (increased to perhaps 13 kkg per year by growth of the industry) is projected for the 1983 time period. The additional abatement cost to the industry is estimated as $19,000 per year for environmentally-adequate land disposal; to be added to the existing cost of $60,000 per year for wastewater treatment and to the existing cost for air pollution control.

Heat Stabilizers for Plastics

Cadmium-containing heat stabilizers find widespread use in retarding discoloration due to the breakdown of polyvinyl chloride resin during the molding operation. Without stabilizers, HCl starts to evolve at about 95°C, and discoloration of the resin occurs with a loss of 0.1 per cent HCl. High molding temperatures are needed for polyvinyl chloride because of its relatively high melt viscosity. For rigid compositions (with little plasticizer), a molding temperature of about 230°C is typical; for flexible compositions with higher levels of plasticizer, molding temperatures of

150°C are typical. Recently, multi-screw extruders have been developed which reduce the temperature-time exposure of PVC resins, thereby reducing the stabilizer requirement by 50 to 74 per cent.(36)

There are four major categories of heat stabilizers for PVC. First are metal soaps of zinc or cadmium, which prevent early discoloration for a short period of time, after which discoloration proceeds rapidly. Second are metal soaps of calcium or barium (or lead), which are not effective in preventing early slight discoloration but which resist serious discoloration for substantially longer periods. Combinations of these two types of stabilizers are effective in preventing both early and later discoloration; actually, their longer-time effectiveness is much greater together than would be expected from the effect of each alone.

This synergism may be illustrated by the following data:(36)

Parts per 100 of PVC Resin		Heat Stability, Minutes
Barium Ricinoleate	Cadmium Ricinoleate	
3.0	0.0	420
2.0	1.0	780
1.5	1.5	720
1.0	2.0	450
0.0	3.0	390

Further synergism is obtained by the addition of a third category of stabilizers to the above two. This third category includes epoxy compounds and phosphites, which have no color-retarding effect by themselves but which appreciably increase the effectiveness of the metal carboxylate stabilizers. The fourth category of heat stabilizers are the organotin compounds, which are extremely effective at low concentrations.

The barium-cadmium stabilizers presently dominate the flexible PVC market. They are used extensively for calendering and plastisols. The lead stabilizers are used primarily for electrical products because of their low water absorption. Calcium-zinc stabilizers are used primarily for food-grade flexible PVC, since the Food and Drug Administration does not permit the use of barium-cadmium (or lead) in food-contacting (packaging) applications. The tin stabilizers find use in rigid PVC formulations; the FDA permits the use of octyl tin stabilizers for bottles, and they are used for PVC pipe and conduit.

The stabilizers vary widely in price:(29)

Barium - cadmium stabilizers,	$0.65 - $1.30/kg
Calcium - zinc stabilizers,	$1.10 - $2.20/kg
Butyl tin stabilizers,	$2.75 /kg
Octyl tin stabilizers,	$6.00 /kg

The consumption of heat stabilizers, of total PVC resin, and of the elemental cadmium consumed in heat stabilizers, is listed in Table 16. The consumption of all heat stabilizers is between 2.0 and 2.5 per cent of the PVC resin consumption; and the barium-cadmium stabilizers have accounted for almost 50 per cent of the total stabilizers consumed. Furthermore, the average cadmium content in barium-cadmium stabilizers is about 7 per cent.

The dominance of barium-cadmium stabilizers has been the combined result of good performance and lowest cost. The organotin stabilizers have superior performance characteristics, but they are relatively higher priced per unit of resin processed despite lower stabilizer requirements. Calcium-zinc stabilizers are used as direct substitutes for barium-zinc stabilizers in flexible food packaging, and the FDA has proposed (Federal Register, April 12, 1974) extending the ban on cadmium colorants and stabilizers to food-contact articles in household, food service, and food-dispensing use (containers, pitchers, tumblers, measuring scoops, mixing bowls, canisters, butter dishes, ice buckets, etc.). The plastics industry, responding to increased pressure based on toxicological reasons, has been developing calcium-zinc stabilizer formulations which, taking advantage of the synergistic action of other ingredients, are approaching the performance of the barium-cadmium stabilizers.

TABLE 16

CONSUMPTION OF HEAT STABILIZERS

SOURCE: MODERN PLASTICS(29)

Data in Thousands of Metric Tons Per Year

	1969	1970	1971	1972	1973
Barium-Cadmium Stabilizers	16.3	16.6	17.3	18.8	20.0
Calcium-Zinc Stabilizers	0.86	0.91	1.00	1.05	1.11
Lead Stabilizers	13.1	13.6	14.1	15.35	16.1
Tin Stabilizers	2.58	2.77	3.45	4.04	4.85
Total Stabilizers	32.8	33.9	35.9	39.2	42.0
Total PVC Resin	1,299	1,385	-	1,975	2,151
Cd in Stabilizers	1.4	1.0	1.2	1.2	-

In summary, then, it appears that the organotins are at present direct substitutes for the cadmium-containing stabilizers; but are higher-priced. In addition, the calcium-zinc stabilizers have already been substituted for the barium-cadmium stabilizers where food considerations have demanded, and the technology appears close at hand to permit the complete substitution of calcium-zinc for barium-cadmium in terms of both performance and costs. The apparent regulatory alternative, therefore, is a complete ban on cadmium-containing heat stabilizers, with perhaps a two-year transition period for industry to accomplish the substitution.

SECTION VII

NICKEL-CADMIUM BATTERIES

The manufacture of nickel-cadmium storage batteries is the fastest-growing segment of the cadmium industry. The demand for nickel-cadmium batteries almost doubled in 1973 and is expected to settle into an annual growth pattern of between 15 and 20 per cent over the next few years. A major constraint to even more rapid expansion is the limited availability of cadmium to the battery industry.

In 1972, a total of 16.3 million nickel-cadmium batteries were produced (11.7 million sealed and 4.6 million vented). The total value of shipments was 47.6 million dollars. The total 1972 production of nickel-cadmium batteries was 4,005.6 kkg. Battery sizes ranged from small button cells less than 14 mm in diameter to large rectangular cells of 113 mm high by 91 mm long by 38 mm wide. Ten plants produce nickel-cadmium batteries; the four largest are General Electric (Gainesville, Fla.), Burgess Division of Gould (St. Paul, Minn.), Union Carbide (Cleveland, Ohio), and Marathon (Waco, Tex.)

Nickel-cadmium rechargeable storage batteries are used for alarm systems, emergency lighting, calculators, pacemakers, portable appliances and tools, walkie-talkies, and for heavy equipment uses in buses, diesel locomotives, airplanes, and spacecraft. Calculators are currently the biggest market for the battery. A new nickel-cadmium cell, introduced in 1973, charges to 90 per cent of its capacity in 15 minutes and is useful for portable garden and power tools and for hobby equipment.

There are two distinct types of nickel-cadmium cells — the pocket plate (Jungner type) cell and the sintered plate cells. Industry sources have indicated that only a limited number of pocket plate type batteries are now being produced in the U.S. The production has switched to the sintered plate cell.

The positive and negative plates of the pocket plate cell are usually similar in construction, consisting of perforated pockets which contain the active materials. The pockets for both positive and negative plates are made from nickel-plated perforated steel ribbon. Pockets of the negative plates are filled initially with cadmium oxide or cadmium hydroxide, either of which is reduced to metallic cadmium on charging. Some manufacturers of these cells add iron (5 to 30 per cent) to the cadmium in order to obtain the required degree of fineness of the cadmium. The pockets of the positive plate are filled with nickel powder.

Wilson(37) dismantled a number of 36 kilogram aircraft batteries and analyzed their constituents:

Cadmium	8.1 per cent
Nickel	25.3 per cent
Iron	6.5 per cent
Cobalt	0.5 per cent
KOH electrolyte	16 per cent

The plates were separately analyzed:

Negative Plate, 39.9% Cd, 42.9% Ni

Positive Plate, 2.2% Cd, 76.2% Ni

The half-reactions of the nickel-cadmium cell are:

Negative Plate, $2NiOOH + 2H_2O + 2e^- = 2Ni(OH)_2 + 2OH^-$

Positive Plate, $Cd + 2OH^- + Cd(OH)_2 + 2e^-$

The cell must be protected against absorption of carbon dioxide from the atmosphere; otherwise, $CdCO_3$ and $NiCO_3 \cdot NiO$ are readily formed.

Industry sources indicate that the production of pocket-plate type batteries does not generate any water-borne hazardous waste. This is because the active chemicals used are solids and not solutions or pastes. When good housekeeping methods are used within the plant, cells rejected in quality control operations are the only waste generated. These cells are reclaimed through sale to scrap processors.(38)

The manufacture of sintered plate batteries, however, does generate hazardous waste. This type of cadmium battery differs materially in construction and performance from the pocket plate battery described above.

This variety of battery contains a cadmium anode, a potassium hydroxide electrolyte, and a nickel oxide cathode. For the electrodes, sintered placques containing the active materials are used. In one process, the placques are made by impregnating binder materials with nickel and cadmium nitrate salts. The nickel and cadmium nitrates are converted to hydroxides in potassium hydroxide solution. The plates are then washed thoroughly and dried in a hot oven. The impregnation cycle is repeated to deposit the desired amount of active material. The plates then go through a formation treatment which removes impurities and brings the active materials to a condition similar to that existing in working electrodes. The cell is assembled into final form using an absorbent plastic separator and a nickel-plated steel case. With the addition of the alkaline electrolyte, they are ready for electrical testing, packing, and shipping.

There are currently three distinct manufacturing processes used for preparing the electrodes of the sintered plate batteries. The preceding paragraph described the worst case from an environmental standpoint of the three, due to the high concentration of cadmium and nickel compounds contained in the wash water. The other processes in use are:

a) An electrolytic deposition process which deposits active materials directly on the sintered plates - this process produces wastewater containing nickel and cadmium compounds, though the amount is not as great as in the impregnation process described above; and

b) A pressed powder process involving active materials mixed with binders in a dry powder form - the powder mix is pressed onto a wire mesh or expanded metal grid in a mold. This is a dry process and no wastewater is involved.

A mass-balanced process flow diagram for the impregnation-sintered plate process is shown in Figure 4. The wastes from the production of this type of battery include the following:

a) Wastewaters containing cadmium and nickel salts together with potassium hydroxide. The source of this waste is the washing steps. This waste is estimated to amount to 3.24 kg nickel nitrate and 7.96 kg cadmium nitrate per 1000 kg of product in the untreated wastewater.

b) Solid wastes recovered from treatment of wastewaters. These are estimated to contain cadmium hydroxide (5.339 kg) and nickel hydroxide (1.660 kg) per 1000 kg of product; and

c) Rejected batteries from the test and package step. They contain 1.47 kg nickel and 5.20 kg cadmium per 1000 kg of product.

This data represents information supplied by three plants representing 42 per cent of the U.S. production. The waste factors for nickel and cadmium in the rejected cells were calculated from plant supplied data. The waste factors for cadmium hydroxide and nickel hydroxide in the wastewater treatment sludge were estimated on the basis of the amount of cadmium in the treated effluents from two plants and the reported efficiencies of the impregnation process.(38)

The total quantity of cadmium in the sludges from wastewater treatment and in the scrap battery waste stream is 9.30 kg per kkg of product. These two solid waste streams are not, however, universally destined for land disposal; an estimated 50 per cent of the plants sell wastewater treatment sludges for reclamation, and an estimated 75 per cent of the plants

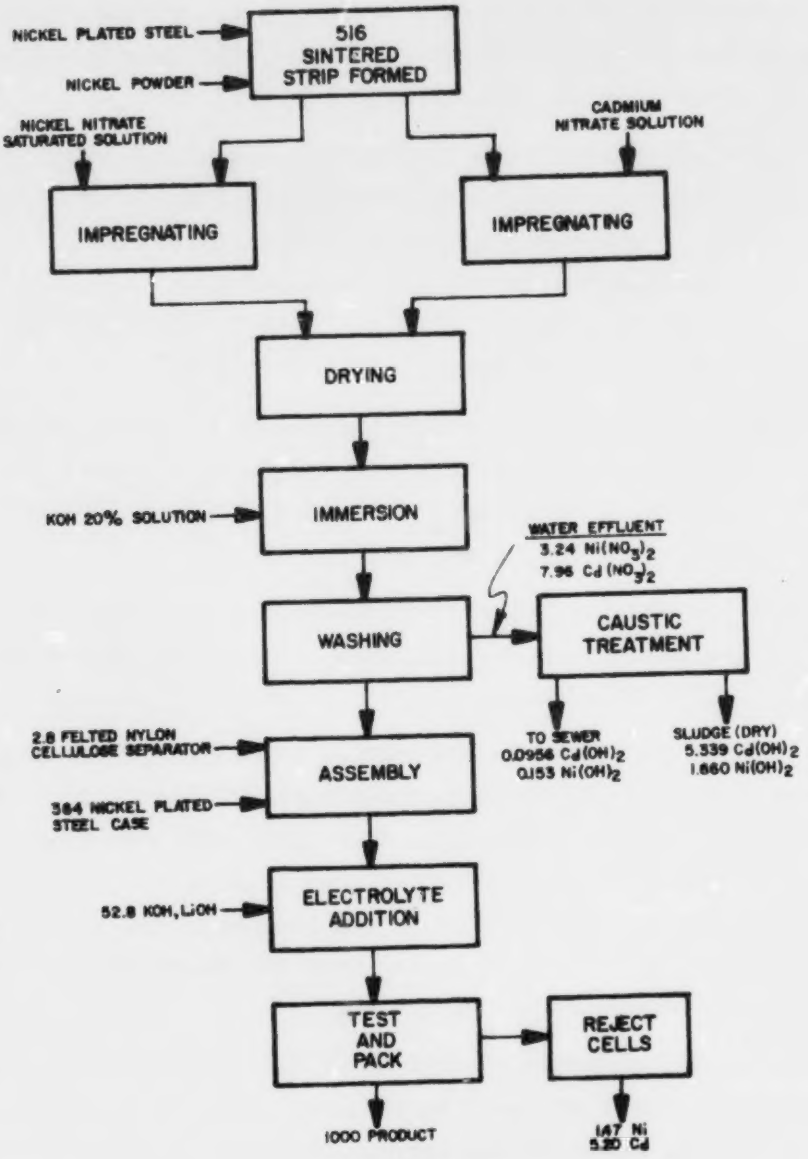
NICKEL PLATED STEEL
NICKEL POWDER
516 SINTERED STRIP FORMED
NICKEL NITRATE SATURATED SOLUTION
CADMIUM NITRATE SOLUTION
IMPREGNATING
IMPREGNATING
DRYING
KOH 20% SOLUTION
IMMERSION
WATER EFFLUENT
3.24 $Ni(NO_3)_2$
7.96 $Cd(NO_3)_2$
WASHING
CAUSTIC TREATMENT
TO SEWER
0.0956 $Cd(OH)_2$
0.153 $Ni(OH)_2$
SLUDGE (DRY)
5.339 $Cd(OH)_2$
1.860 $Ni(OH)_2$
2.8 FELTED NYLON CELLULOSE SEPARATOR
ASSEMBLY
384 NICKEL PLATED STEEL CASE
52.8 KOH, LiOH
ELECTROLYTE ADDITION
TEST AND PACK
REJECT CELLS
1000 PRODUCT
147 Ni
520 Cd

FIGURE 4

SIMPLIFIED DIAGRAM OF MAJOR OPERATIONS IN NICKEL-CADMIUM SINTERED-PLATE STORAGE BATTERY MANUFACTURE sell reject batteries to reprocessors. As a result of the above solid waste factors and of the estimated extent of reclamation, the total quantity of cadmium (as elemental Cd) disposed of on land in 1973 was estimated as 8.4 kkg. This disposal is currently environmentally inadequate, consisting of simple land dumping and on-site ponding of sludge, since leaching and contamination of both surface and ground waters are probable. Such disposal methods are estimated to cost $133 per metric ton of solid waste (dry basis), or $320 per metric ton of elemental cadmium in the waste; for a total 1973 cost of $2,700.

The projected quantity of cadmium (for 1977) to be disposed of on land in the same inadequate manner is 11.4 kkg; the increase over 1973 due to a projected growth of the industry is partially offset by some increase in either reclamation of the wastes or secured land disposal. The disposal costs would amount to $3,700.

By 1983, it is projected that no solid wastes will be disposed of on land in an environmentally unacceptable manner. In all likelihood (especially in view of the increased price and short supply of cadmium) most of the cadmium in the industry's solid wastes will be reclaimed; where reclamation is impractical, either secured landfill or chemical fixation of sludge should cost $200 per metric ton of solid waste (dry basis), or $480 per metric ton of elemental cadmium in the waste. The projected quantity of cadmium to be disposed of by 1983 is 9.1 kkg, so that the total cost would be $4,400.

These total disposal costs are low chiefly because the cadmium-containing wastes are highly concentrated; this is quite a different situation from many where the hazardous contituent is dispersed in a much larger quantity of other materials.

According to Figure 4, the treated wastewater still contains 0.0735 kg of elemental cadmium per kkg of product; at a 1973 production level of 4005.6 kkg, the cadmium loss to wastewater amounts to 0.294 kkg per year.

According to Davis,(11) the cadmium emissions to the atmosphere from the manufacture of nickel-cadmium batteries is 1 kg per kkg of cadmium charged. Hence, the annual emission to the atmosphere is about 1 kkg.

Wilson[(37)] investigated the reclamation of cadmium from discarded batteries and reported 94 per cent cadmium recovery. This process was based upon a roasting step at 288° to 316°C (550° to 600°F), a leaching of the cadmium oxide with ammonium nitrate to form the highly soluble $Cd(NH_3)_4^{+2}$ complex ion and subsequent precipitation of cadmium carbonate with carbon dioxide. Alternately, 99 per cent recovery of cadmium from the plates was achieved by vacuum distillation (0.1 mm Hg at 650° to 800°C). These emerging technologies, plus the existing reclamation of prompt battery scrap, plus the stripping technology used in the cadmium electroplating industry, provide evidence that recycling of nickel-cadmium batteries is technically feasible. The institutional aspects of battery recycling are already in effect for larger storage batteries (i.e., the lead-acid battery industry regularly practices trade-in as well as recovery from junk automobiles). However, the mechanism for recovery of spent smaller batteries (a large proportion of the nickel-cadmium battery market) is not yet developed.

In addition to the cadmium reclamation technologies of vacuum distillation and leaching with an ammonium salt, another process is amalgam electrolysis. Many companies are now processing nickel-cadmium battery scrap but primarily for the nickel values rather than for the cadmium values. It appears, then, that as the nickel-cadmium battery use increases, a commeasurate increase in reclamation will follow. A special incentive such as a refundable deposit, or a requirement for nickel-cadmium batteries to be labelled with reclamation instructions, are two ways to encourage recycle of used batteries.

SECTION VIII

SECONDARY METALS INDUSTRY

Secondary Non-Ferrous Metals

The secondary zinc and copper industries may initially be suspect as a source of cadmium pollution because of the high-temperature processing involved. The Bureau of Mines Office of Mineral Resource Evaluation estimates that in the 28-year period from 1940 to 1968 the accumulation of these metals in the in-use reservoir was 23,200,000 kkg of copper and 3,820,000 kkg of zinc. Of this reservoir, the secondary metals industry processed (in 1967) the quantities listed in Table 17.

Although the total zinc-base scrap processed amounts to 155,000 kkg per year, the bulk of the scrap is zinc die-casting alloys. These alloys utilize special high-grade zinc only, which contains no more than 0.004 per cent cadmium. Hence, the cadmium in the zinc-base secondary metals processed amounts to an estimated 6.2 kkg. In addition, since the basic recovery process for secondary zinc is distillation and collection of zinc and zinc oxide, effective dust collection is universally practised. At a 90 per cent collection efficiency, the quantity of cadmium emitted would be only 0.6 kkg per year.

A total of 1,168,000 kkg per year of copper-base scrap is processed in high-temperature blast furnaces, melting furnaces, and sweating furnaces; of which 60 per cent is brass and bronze (the remaining 40 per cent contains no cadmium).(39) The zinc content of these alloys is as follows:

	Per Cent Zinc
Commercial bronze	10
Red brass	15
Low brass	20
Cartridge brass	30
Yellow brass	35
Muntz metal	40

TABLE 17

SECONDARY COPPER AND ZINC PROCESSED IN 1967

SOURCE: SPENDLOVE[(39)]

	Secondary Copper	Secondary Zinc	Secondary Cu + Zn Totals
New Scrap (Total)	605,000 kkg	215,000 kkg	820,000 kkg
Copper-Base	605,000	97,000	702,000
Zinc-Base	0	118,000	118,000
Old Scrap (Total)	433,000	70,000	503,000
Copper-Base	433,000	33,000	466,000
Zinc-Base	0	37,000	37,000
Total Copper-Base	1,038,000	130,000	1,168,000
Total Zinc-Base	0	155,000	155,000
Grand Totals	1,038,000	285,000	1,323,000

Free-cutting brass	34
Naval brass	39
Architectural bronze	40

Of the 1,168,000 kkg per year of copper-base scrap processed, 60 per cent is brass or bronze.(28) If these alloys contain an average of 30 per cent zinc, the quantity of zinc in processed scrap is 210,000 kkg per year. However, much of this zinc is directly reused in the production of secondary copper alloys; in 1971, a total of 148,000 kkg of secondary zinc (70 per cent of the total processed) was so used. The remainder of the secondary zinc processed, 62,000 kkg per year, is refined at high temperatures, and the cadmium in this zinc would be in the form of dusts and fumes.

Although the ASTM grades of zinc primarily used for copper-based alloys permit up to 0.5 per cent cadmium, the data of Tables 7 and 8 indicate that pyrometallurgical zinc contains no more than 0.035 per cent cadmium, and electrolytic zinc typically contains 0.00002 per cent cadmium. At the higher cadmium level, the 62,000 kkg of refined secondary zinc would contain 22 kkg of cadmium; and if the dust collection efficiency were 90 per cent, the quantity of cadmium emitted would be 2.2 kkg per year.

This estimate of cadmium loss may be high since the cadmium content of secondary copper-base metals might be appreciably lower than was assumed. For one, much of the zinc in the scrap brass and bronze might actually be electrolytic, with much less cadmium than the assumed 0.035 per cent. For another, it must be recognized that the recycle ratio of copper-base metals is quite high; from 1967 through 1971, the secondary copper production was about equal to domestic mine production. The implication of this extensive recycling is that the cadmium in scrap can, of course, only be lost once; secondary brass as scrap must contain less cadmium than primary brass as scrap.

It must be emphasized that the cadmium concerns in the non-ferrous secondary metals industry are not the result of the intentional use of cadmium (i.e., cadmium electroplating), but are the direct result of the cadmium impurity in zinc/copper alloys. One potential regulatory posture would be to require the use of only high-grade zinc in the production of primary brass and bronze; i.e., to prohibit the use of high-cadmium zinc for these alloying purposes. Although a significant time lag would be involved before the total effects are felt in the secondary metals industry (since there is so much recycling of copper-base metal), this alternative regulation would in the long run prove most effective. The technology for almost totally removing cadmium at the primary zinc source is proven and economical electrolytic plants are now favored over retort plants for reasons other than eliminating cadmium pollution. Conversely, regulations aimed at the secondary copper-base metals industry to strengthen existing air pollution control regulations (i.e., to enforce universal use of baghouses to collect cadmium-bearing dusts) would be an alternative with shorter-term effectiveness.

Secondary Ferrous Metals

Cadmium enters the primary iron-and-steel industry as cadmium-bearing ferrous scrap, in the form of cadmium electroplate or cadmium-contaminated galvanized coatings. The cadmium is entirely volatilized at steel-making temperatures so that the product steel contains no cadmium. Some of the cadmium is released to the environment via the inefficiencies in dust-catching equipment, while the cadmium in the captured dusts may also enter the environment because of inadequate disposal and/or use of these dusts.

Previous estimates of the quantity of cadmium involved in steelmaking(1,11) used aggregate data for a cadmium-to-steel ratio in scrap, basically derived from the total quantities of cadmium used in electroplating and galvanizing as compared to the total quantities of steel produced. The estimate made in this study is intended to differentiate among steel products consumed so that a cadmium-to-steel ratio specific to scrap may be estimated and used.

The ferrous scrap specifications for No. 1 heavy melting steel, No. 1 bundles, and other No. 1 grades exclude scrap that is metal coated and old automobile body and fender stock.(40) It is clear, therefore, that No. 1 ferrous scrap contains no cadmium. No. 2 scrap (heavy melting and bundles) is the grade where auto stock and other coated iron and steel is classified; actually, No. 2 scrap is largely composed of obsolete auto and truck bodies.

Approximately 7 million junk automobiles per year are processed by the secondary ferrous metals industry.(41) A typical junk automobile, weighing 1,450 kg, yields 1,150 kg of No. 2 bundle steel.(40,41) Hence, junk automobiles are the source for about 8 million metric tons per year of No. 2 ferrous scrap. Table 18 lists the recent movement of No. 2 scrap.(28,40)

These data show that the 8 million kkg per year of No. 2 scrap from auto bodies constitutes about 85 per cent of all domestic generation of old No. 2 scrap, and about 75 per cent of all such scrap (including the home scrap). Hence, the assumption that the cadmium content of the No. 2 scrap consumed in steel making is equivalent to the cadmium content of auto scrap is justified.

The discussion of electroplating resulted in a cadmium content of 50 grams per auto via electroplated steel. Virtually all should show up in the No. 2 ferrous scrap portion of the processed junk auto, since no cadmium plating of nonferrous metal (or plastics) is conducted. The question also arises whether cadmium from sources other than electroplating is in an automobile. Cadmium colors and stabilizers in the polyvinyl chloride would not be retained in the ferrous scrap portion; the plastic would either be burned off or left behind in the magnetic recovery of a shredded auto. Similarily, cadmium in the zinc oxide of tires would not be carried with the No. 2 scrap portion.

TABLE 18

USE OF NO. 2 SCRAP, MILLIONS OF METRIC TONS PER YEAR

		Receipts by U.S. Iron & Steel Industry	U.S. Exports	Total, Receipts & Exports	Produced Scrap, U. S. Iron and Steel Industry	Consumed Scrap, U. S. Iron and Steel Industry
1970	No. 2 Heavy Melting	2.90	1.03	3.93		2.93
	No. 2 Bundles	3.35	1.25	4.60		3.55
	Shredded	0.72	1.06	1.78		0.76
	TOTAL	6.97	3.34	10.31		7.24
1971	No. 2 Heavy Melting	2.06	0.58	2.64	0.96	2.97
	No. 2 Bundles	2.44	0.89	3.33	0.48	2.89
	Shredded	1.52	0.93	2.45	0.00	1.50
	TOTAL	6.02	2.40	8.42	1.44	7.36
1972	No. 2 Heavy Melting	2.13	0.68	2.81	1.01	3.10
	No. 2 Bundles	2.95	0.81	3.76	0.48	3.34
	Shredded	1.87	1.33	3.20	0.00	1.87
	TOTAL	6.95	2.82	9.77	1.49	8.31

A typical auto contains 25 kg of zinc die-cast alloy,(40) but at a maximum cadmium concentration of 0.004 per cent(23) for the Special High Grade used in die-casting, the quantity of cadmium per auto would amount to only one gram. Moreover, much of the Special High Grade zinc is electrolytic, with a typical cadmium content of 0.00002 per cent,(3,5) much less than the maximum; and in any event, most of the zinc die cast alloy is not carried with shredded ferrous scrap but is rejected by the magnetic separation.(42) Hence, compared to the cadmium from electroplated steel, the cadmium from zinc die cast may be neglected.

The cadmium in an auto's galvanized parts most likely would be carried into the processed ferrous scrap. Prime Western grade zinc, used widely for galvanizing, typically contains 0.035 per cent cadmium.(5) The quantity of galvanizing zinc used for automobiles is not directly known, but a maximum value may be obtained by difference. In 1968, the consumption of all zinc by the transportation industry was 360,000 metric tons.(43) It has also been estimated that of the total die-cast alloy consumed (500,000 kkg), approximately 60 per cent (or 300,000 kkg) is consumed by automobile manufacturers.(43) Hence, the zinc consumption by automobile manufacturers for galvanizing is no greater than 60,000 kkg per year; equivalent to 5 kilograms per car. The maximum amount of cadmium, then, would be 1.75 grams per car from galvanizing.

The conclusion reached, then, is that the total quantity of cadmium per car distributed in the 1,150 kg of No. 2 scrap is 52 grams; and so the cadmium concentration of No. 2 scrap is deduced to be 0.045 kg per metric ton.

Based upon the above reasoning, the conclusion that only No. 2 scrap contains cadmium, and the annual consumption of No. 2 scrap by the iron and steel industry (about 7.6 million metric tons per year), the calculated quantity of cadmium entering the iron and steel industry is 340 metric tons per year.

Other estimates have been made based upon aggregate factors for the concentration of cadmium in scrap iron and steel. Davis(11) used concentration factors of 0.025 kg cadmium from electroplating and 0.0015 kg cadmium from galvanizing per metric ton of all old steel scrap; which when applied to a consumption of 35 million metric tons per year of old scrap yielded a quantity of cadmium entering the iron and steel industry of 930 metric tons per year. Fulkerson(1) recalculated this quantity based upon concentrations of cadmium in finished steel to be 0.037 (electroplated) and 0.00125 (galvanized) kg per metric ton; and an annual consumption of 26 million metric tons of steel scrap; to yield a quantity of cadmium entering the iron and steel industry of 990 metric tons per year.

An independent estimate of the quantity of cadmium involved in steel-making was made in this study, using the uncontrolled dust emission factors for each process of EPA,(21) the 1972 and 1985 steel production statistics for each process,(28,40) and the experimental cadmium concentrations in flue dusts from each process of Yost:(4)

		Open Hearth	Basic Oxygen	Electric Arc	Total
Dust Produced, kg/kkg steel		4.15	25.5	4.6	-
Steel Produced, Million kkg/yr	1972	31.7	67.6	21.5	120.8
	1985	12.7	115.2	53.5	181.4
Cd concentration in dusts, ppm		250	80	580	-
Dust Produced, kkg/yr	1972	132,000	1,720,000	99,000	1,951,000
	1985	53,000	2,940,000	246,000	3,239,000
Cd in Dusts, kkg/yr	1972	33	137	57	227
	1985	13	235	143	391

The total cadmium, 227 kkg/yr (1972) and 391 kkg/yr (1985), is in good agreement with the 340 kkg/yr estimated from the analysis of scrap flow, and verifies this lower estimate (as compared to previous estimates). The total quantity of dusts is very high; at an average cost for secured landfill of $70 per metric ton, the costs for land disposal in an environmentally adequate manner (considering the high cadmium concentrations) are:

1972, $137 million per year
1985, $227 million per year

The lower quantity (340 kkg per year) calculated in this study is believed to be the more precise value because it is based upon the specific scrap grade that contains cadmium rather than upon aggregate values for all scrap. The data of Yost(4) at an open hearth furnace with an electrostatic precipitator yielded a factor of 0.085 x 10^{-6} kkg of cadmium emissions per kkg of steel produced; or a factor of 1.4 x 10^{-6} kkg of cadmium emissions per kkg of No. 2 scrap consumed at this furnace. Applying this factor to the total U.S. consumption of No. 2 scrap, 7.6 million kkg per year, yields a cadmium emission from the iron and steel industry of 10.5 kkg per year. This emission is 3.1 per cent of the 340 kkg/year of cadmium entering the industry in No. 2 scrap; a percentage entirely consistent with the operating efficiencies achieved by electrostatic precipitators.

The data of Yost(4) for the cadmium concentrations in the collected dusts from the three major steel processes show a direct correlation with the relative quantities of scrap used in the charge:

	Total Scrap Used, kkg per kkg of Product	Cd Concentration in Collected Dusts, ppm
Open Hearth	0.50	250
Basic Oxygen	0.33	80
Electric Furnace	1.00	580

The reason for this wide variation is fundamentally that the carbon in pig iron is a fuel in the open hearth and basic oxygen processes for providing the required heat in steel making. The basic oxygen process utilizes more of this heat of combustion, thereby conserving auxiliary fuel, than the open hearth process. Hence, the basic oxygen process needs more carbon-containing pig iron (and therefore may use less scrap) than the open hearth process. At the other extreme, the electric furnace process provides all of the heat from an auxiliary source, and therefore may use 100 per cent scrap. Recent efforts have been directed towards increasing the allowable scrap content of the basic oxygen process, by preheating the scrap and by adding a fuel such as calcium carbide.

On the other hand, the utilization of No. 2 scrap is product-oriented. The permissible level of No. 2 scrap, regardless of process, is determined by the permissible level of impurities in the product steel. Copper, nickel and tin are neither removed in the steel making slag (as is aluminum), nor are they removed by vaporization (as is Cd, Zn, and Pb); they are carried through to the finished steel. The desired copper content of finished steel is:(40)

Low quality steels,	0.5 per cent
Average quality,	0.3 per cent
High quality,	0.1 per cent
Deep-drawing quality,	0.05 per cent

In contrast, the copper content of ferrous scrap is:(40)

No. 1 Factory Bundles,	0.06 per cent
No. 1 Industrial Heavy Melting,	0.10 per cent
No. 1 Railroad Heavy Melting,	0.16 per cent
No. 1 Dealer Bundles,	0.12 per cent
No. 2 Car Sides, Bundles,	0.27 per cent
No. 2 Dealer Heavy Metal,	0.40 per cent
No. 2 Dealer Bundles,	0.48 per cent
No. 2 Shredded Scrap,	0.22 per cent

Other factors influence the utilization of No. 2 scrap. One is the availability of home scrap in the steel mill; the use of purchased scrap (including No. 2 scrap) may be influenced by the difference between total scrap requirements and home scrap availability. Another factor is that the impure No. 2 scrap requires more fuel, more heat time, and more lime than factory bundles. A very important factor is that No. 2 scrap introduces uncertainty into steel making; a margin of safety is applied so that the highly-variable impurities of No. 2 scrap do not compromise product quality.

In projecting the flow of cadmium into steel making via No. 2 scrap, two points must be made. First, the recent efforts towards improving the quality of No. 2 scrap (i.e., shredding and magnetic separation) may increase the utilization of No. 2 scrap; the cadmium content of the scrap would not be lowered by these techniques, so that more cadmium would flow into steel making. Second, the recent growth of the electric-furnace "minimills" scattered around the country and heavily utilized to make lower-grade steels from local No. 2 scrap would decentralize the cadmium flow and therefore make it more difficult to control. As the data of Table 19 indicate, the steel industry has been experiencing a major change in the relative importance of the three major processes.

In past years, the collected dusts from steelmaking furnaces (which contain iron oxide) were sent to the sintering plants along with ore fines, coke breeze, limestone and recycled material from various mill processes. The purpose of the sintering process is to form larger agglomerates from the fines for recycle to the blast furnace. However, the sintering operation has been under recent attack because of its poor record of air pollution, and the recent trend has been to dispose of cadmium-bearing furnace dusts as landfill rather than to recover the iron values by sintering and recycling. Little is presently known of the environmental hazards of land-destined dusts containing cadmium, which of course involve much more cadmium than the cadmium emitted to the atmosphere.

TABLE 19

CHANGE IN STEEL PRODUCTION FOR EACH MAJOR PROCESS

SOURCES: BUREAU OF MINES,(28) REGAN(40)

Year	Production, Millions Metric Tons Per Year			
	Open Hearth	Basic Oxygen	Electric	Total
1950	78.1	--	5.4	83.5
1955	95.5	0.3	7.3	103.1
1960	78.3	3.0	7.6	88.9
1965	85.5	20.8	12.5	118.8
1968	59.6	44.3	15.3	119.2
1969	55.1	54.6	18.2	127.9
1970	43.5	57.4	18.3	119.2
1971	32.2	57.9	19.0	109.1
1972	31.7	67.6	21.5	120.8
1980*	22.7	95.2	40.8	158.7
1985*	12.7	115.2	53.5	181.4

*Projections

The sintering operation itself, being a high-temperature process, results in some cadmium being released to the atmosphere despite dust control equipment. In this case, from the standpoint of cadmium (as opposed to total dusts), the sintering operation is contraproductive, since double exposure of furnace dusts occurs (once in the furnace and once in the sinter plant). The cadmium in the furnace dusts that winds up in the sintered agglomerates is most likely an ultimate constituent of the blast furnace slag (if it is not emitted again as blast furnace dust or even downstream as steel furnace dust).

Apparently the cadmium in the ferrous scrap, being relatively volatile, is exposed to at least one and possibly multiple high-temperature operations where some of it escapes to the atmosphere. Since no cadmium leaves the steel mill with the steel, the cadmium not lost to the atmosphere is a constituent of other waste streams from the steel mill.

Several regulatory alternatives are suggested to control the release of cadmium into the environment from the steel industry:

1. Banning or severely restricting the use of cadmium electroplating in automobile manufacturing. If technically feasible, this option would effectively reduce the flow of cadmium into steel making since auto scrap is the dominant route.

2. Stringent air pollution control regulations for steel making, including the mini-mills. A dust capturing efficiency of 97 per cent or better should be imposed. It may be feasible to impose guidelines in terms of cadmium emissions permitted per unit of No. 2 scrap used. If a guideline was based on the finished steel production level, the effect would be a disincentive for using No. 2 scrap.

3. Stringent regulations regarding the handling and disposal of the collected dusts from steel making, since this waste stream contains the bulk of the cadmium. The fine dusts should be prevented from being dispersed by the wind or by storm water drainage. Land disposal should be adequately protected so that surface and ground waters are not contaminated. Research aimed at recovering the cadmium (and zinc and lead) values, as well as the iron values in this steel making dust, should be encouraged.

SECTION IX

CADMIUM AS AN IMPURITY

The dissemination of cadmium to the environment is attributable not only to the production and use of cadmium and its compounds as discussed in the previous sections, but also to the unintentional prevalence of cadmium as an impurity in several important materials.

Rubber Tires

The estimate of cadmium emissions from rubber tire wear made by Davis,(11) widely quoted by others,(1,2,44) is 5.2 metric tons per year. This estimate is based upon a cadmium content in tread rubber of 20 ppm, a loss of 1.27 kg of tread rubber per tire in 32,200 km (20,000 miles) of use, and a total United States travel of 1.62 x 10^{12} vehicle-kilometers (1.01 x 10^{12} vehicle-miles).

The source of cadmium in rubber tires is the cadmium impurity in the zinc oxide, which is used as an activator for organic accelerators for the vulcanization process. From 3 to 5 kilograms of zinc oxide are used per hundred kilograms of rubber. Table 20, which lists the recent consumption data for zinc oxide, shows that 53 per cent of the total is used in rubber manufacturing.

Three processes are in use for making zinc oxide. The American, or direct process, for making zinc oxide is similar to the primary zinc process; it is made from roasted zinc ore concentrate. As in the primary zinc process, the roasted ore is sintered with coal and the sinter is then retorted. In the manufacture of zinc oxide, the retorting is conducted in the presence of air, so that finely-divided zinc oxide is recovered rather than molten zinc. In the French, or indirect, process variation, zinc metal is first recovered, then vaporized and oxidized. The third process is a proprietary wet process for purifying crude zinc oxide recovered from lead smelters.

TABLE 20

CONSUMPTION OF ZINC OXIDE
SOURCE: BUREAU OF MINES (28)

	Total Consumption, kkg/year	Consumption in Rubber, kkg/year
1967	165,000	86,000
1968	194,000	101,000
1969	199,000	105,000
1970	193,000	101,000
1971	206,000	113,000
1972	223,000	117,000

The wet process accounts for approximately 10 per cent of the total production.(33) In 1972, 47,100 kkg of slab zinc were used for the production of zinc oxide,(28) so that the French process accounted for 58,700 kkg of zinc oxide, or 26 per cent of the total. Hence, the American process (by difference) accounted for 64 per cent of the total production.

The quantities of impurities in commercial zinc oxide manufactured by St. Joe Minerals are:(5)

	American Process ZnO	French Process ZnO
PbO, %	0.009	0.0015
CdO, %	0.010	0.0006
Fe_2O_3, %	0.015	0.005

A more recently-acquired estimate from an industrial source for American Process ZnO was 100 to 300 ppm of cadmium. Hence, assuming 100 ppm in American Process ZnO and assuming a production level of 150,000 kkg per year of American Process ZnO, there are 15 metric tons per year of cadmium impurity in American Process zinc oxide.

The price differential between the two grades of zinc oxide is rather small (Chemical Marketing Reporter, March 31, 1975):

ZnO pigment, American Process (lead-free),	$0.88 - $0.92/kg
ZnO pigment, French Process (regular),	$0.92 - $0.94/kg

The American (or direct process) zinc oxide contains comparable quantities of cadmium to the metallic zinc products; the processes are directly comparable. The French (or indirect process) zinc oxide contains much less cadmium since a zinc purification step may be added or since electrolytic zinc may be used.

At an average zinc oxide usage ratio of 4 parts per hundred of rubber, the cadmium content of the rubber would be 4 ppm (American ZnO) and 0.2 ppm (French ZnO). These levels are considerably lower than the 20-90 ppm reported for rubber tires by Lagerwerff and Specht,(45) used as a basis for the Davis estimate.(11)

A possible explanation for this large difference in cadmium content (less than 4 ppm vs 20-90 ppm) is that other zinc oxide producers permit higher cadmium concentrations, on the order of 0.05 to 0.25 per cent. This is likely if zinc oxide is made from collected dusts and fumes (which may contain up to 25 per cent cadmium).

The straightforward control strategy would be to regulate the cadmium content of rubber tires to 4 ppm, which would force the cadmium content of the zinc oxide used to 100 ppm or less. Such a regulation, while permitting the use of American process zinc oxide, would reduce the cadmium emissions from the estimated 5.2 kkg per year to approximately 1 kkg per year.

Of course, the corollary regulation would be the stringent control of cadmium emissions from the zinc oxide manufacturing process.

Zinc for Galvanizing

The grades of zinc used for galvanizing contain approximately 0.035 per cent cadmium.(1,5) From 1968 to 1972, the quantity of zinc used for galvanizing has been relatively stable at 450,000 metric tons per year, and has remained at approximately 37 per cent of the total zinc consumed. Hence, it is estimated that approximately 160 metric tons per year of cadmium is unintentionally involved in galvanizing.

Commercial quality zinc coating on steel sheet has an average thickness of about 0.003 centimeters, and the weight of zinc is about 0.191 kg/m^2.(23) More than 50 per cent of all the zinc used for galvanizing is consumed for sheet and strip. However, the specific quantities of zinc vary considerably with the shape of the steel work, as Table 21 indicates.

TABLE 21

GALVANIZING EFFICIENCIES AND COATING WEIGHTS

SOURCE: DAESEN(46)

Product	Zinc Melted, kg/kkg Product	Pct. of Zn Melted Remaining on Work	Coating Weight, Pct. of Product
Sheet	84	83	7.4
Pipe	83	68	6.0
Wire	42	65	2.7
Sheet Ware	228	82	18.6
Wire Cloth	240	80	19.8
Pole Line Hardware	79	45	3.5
Structural	62	67	4.1
Castings	104	48	4.9

Galvanized steel products are used widely in construction; in heating, ventilating and air conditioning; in plumbing, and in many other applications. The corrosion protection afforded by the zinc coating is by two mechanisms: first, because zinc covers the steel (and corrodes more slowly), and second, because in galvanic corrosion, zinc sacrifically oxidizes. The point is that the zinc coating (and of course the 0.035 per cent of cadmium) is expected to be released to the environment.

The data of Table 22 indicate that corrosion is very rapid in atmospheres containing SO_2 and moisture, as in industrial indoor or outdoor use. In only a few (4 to 12) years, all of the cadmium in galvanized coatings in such atmospheres is released to the environment. For estimating purposes, it is hypothesized that the cadmium annually released to the environment is 25 per cent (or 40 kkg/yr) of the cadmium in new galvanized products each year. The remainder is assumed to be in non-corrosive atmospheres, otherwise protected from corrosion (painted or masked by other parts), consumed in the scrap metal industry, or disposed of in the solid waste stream.

As in the zinc oxide case, the straightforward control strategy would be the regulation of the cadmium content. In 1972, virtually 50 per cent of all the slab zinc produced was special high grade,(28) with a maximum cadmium content of 0.004 per cent.(23) Much of this, used primarily in die-cast alloys, was electrolytic zinc. Approximately 60 per cent of the domestic zinc production is pyrometallurgical, and this is the primary source for the lower grades of zinc (Prime Western and Select) that are used for galvanizing.

Some of the pyrometallurgical zinc is presently refined to meet the large market for special high grade zinc. Two processes are in common use for the refining of zinc to remove cadmium: redistillation and electrolytic.(3) An appropriate control alternative, based upon existing technology,

TABLE 22

CORROSION OF ZINC IN VARIOUS ATMOSPHERES

SOURCE: METALS HANDBOOK(23)

	Corrosion, cm/yr	Corrosion, kg/m^2/yr	Life of Common Galvanized Coating, Years
Indoor Industrial (Heat, Moisture)	0.00008	0.005	38
Indoor Industrial (Heat, Moisture, SO_2)	0.00025	0.016	12
Outdoor, arid	0.00003	0.002	100
Outdoor, seacoast	0.00018	0.011	17
Outdoor, highly industrial	0.00069	0.044	4

would be to require that all zinc used meet the 0.004 per cent cadmium specification. This would eventually reduce the cadmium emission from the corrosion of galvanized steel by ten-fold. A long lead time is involved in reducing the cadmium emissions because of the huge quantities of galvanized steel already produced over the years.

As previously stated, such a restriction must be accompanied by restricting cadmium emissions during zinc production.

Given sufficient lead time to enable the industry to install sufficient pyrometallurgical zinc refining capacity, the problem of limiting the cadmium content in zinc may be defined as one of equity between the pyrometallurgical producers and the electrolytic producers.

The current price differential is only about $0.02 per kilogram (American Metal Market, March 24, 1975):

Prime Western Grade,	$0.85 - $0.86/kg
High Grade,	$0.87 - $0.88/kg
Special High Grade,	$0.87/kg

In comparison, it is estimated that in light of increased energy costs, the cost of refining Prime Western zinc would be $0.04 per kilogram. The value of the recovered cadmium (perhaps 0.35 grams per kilogram of zinc) would be no more than $0.003 per kilogram of zinc. Hence, there would be a net penalty of about $0.02 per kilogram for the pyrometallurgical zinc producers as compared to the electrolytic producers.

More must be learned of the economic impacts of a regulation banning the sale of all zinc and zinc products with more than about 40 ppm of cadmium before such a regulation is promulgated. The decision comes down to a case of conflicting inequities. On the one hand, it may be inequitable to penalize the pyrometallurgical zinc producers with respect to the electrolytic zinc producers. On the other hand, it may be inequitable to penalize one class of cadmium dissipators (i.e., requiring costly wastewater treatment for electroplaters to reduce their 80 kkg/year effluent while permitting the zinc industry to dissipate 160 kkg/year of cadmium).

Phosphate Fertilizers

Fulkerson(1) estimated that the cadmium content of commercial phosphate fertilizers (at 2 to 20 ppm) amounted to 23-230 metric tons per year; based upon a 1968-69 consumption of about 11,000,000 kkg per year of fertilizers with a P_2O_5 content of 3,800,000 kkg.

The consumption of fertilizers is expanding at a 5 to 7 per cent growth rate in North America:(47)

1965	3.6 million metric tons P_2O_5/year
1970	5.0 million metric tons P_2O_5/year
1975	6.3 million metric tons P_2O_5/year
1980	8.0 million metric tons P_2O_5/year

Hence, the Fulkerson estimate of cadmium in consumed fertilizers would double before 1980.

The zinc and cadmium concentrations in several commercial fertilizers were measured by Yost:(4)

Fertilizer	Fertilizer Composition	Zinc, ppm	Cadmium, ppm	Zn/Cd
Diammonium Phosphate	18-46-0	122	9.0	13.6
Diammonium Phosphate	16-48-0	160	14.3	11.2
Monoammonium Phosphate	13-52-0	92	3.5	26.3
Triple Super Phosphate	0-46-0	95	7.2	13.2
Composite Data		114	7.8	14.7

It is readily apparent that the Zn/Cd ratio is much lower than the value of 200 normally found in natural materials. Page(2) attributes this to the cadmium accumulations by marine animals from sea water, and the deposition of the hard parts of these animals to form marine phosphorite deposits such as the Florida phosphate fields.

If Yost's composite cadmium concentration of 7.8 ppm is used, this is equivalent to a value of about 16 ppm based on P_2O_5, so that the cadmium estimate for 1975 becomes 100 kkg/year and that for 1980 becomes 130 kkg/year.

The cadmium and zinc in phosphate rock exists as replacement atoms for calcium in the apatite, and so accompany the P_2O_5 in the ore beneficiation process (which concentrates P_2O_5 from 15 to 31 per cent) and in the manufacture of phosphoric acid (by either the wet or dry process). Cadmium and zinc are highly soluble in mineral acids, so that the normal phosphoric acid clarification step does not remove them. The treatment with sulfide to remove arsenic from food-grade phosphoric acid probably would not be effective, since cadmium sulfide has a solubility in the range of 5,000 ppm at low pH.(12) The fate of cadmium in the solvent-extraction commercial process for recovering and purifying phosphoric acid is not known, but it is possible that the cadmium salts are not extracted by the organic solvents, so that they may be separated from the phosphoric acid.(47,48)

For the sake of completeness, the possibility of cadmium entering phosphate fertilizers via the sulfuric acid (in addition to the phosphate ore source) was investigated. It has been previously mentioned that by-product sulfuric acid from zinc smelters may contain 20 to 60 ppm of cadmium.(1) It is also likely that by-product sulfuric acid from copper and lead smelters also contains cadmium in smaller concentrations.

Of the total U.S. sulfuric acid production (in 1973) of 37.2 million metric tons (as 100 per cent H_2SO_4); only 10.9 per cent, or 4.05 million kkg, was produced from all smelter off-gases; and only 2.6 per cent, or 0.97 million kkg, was produced from the roasting of zinc concentrates.(49) The zinc smelters (Table 4) are located in Pennsylvania, Texas, Oklahoma, Idaho, and Illinois — far removed from the Florida phosphate fields; but a significant amount of wet-process phosphoric acid is manufactured close enough to the smelters so that by-product sulfuric acid may conceivably be used.

The total quantity of wet-process phosphoric (as P_2O_5) manufactured in 1973 was 5.7 million kkg.(49) Since approximately 2.8 kkg of 100 per cent H_2SO_4 is required per kkg of P_2O_5,(47) the sulfuric acid consumed in wet-process phosphoric acid manufacture was approximately 16 million metric tons. This is 43 per cent of the total demand for sulfuric acid, enhancing the probability that at least some zinc smelter acid is being used for fertilizer manufacture.

The possibility was also investigated for cadmium entering the fertilizer process via an impurity in elemental sulfur used for sulfuric acid manufacture. This possibility was discounted, however, as Frasch process sulfur typically contains less than 5 ppb of cadmium.(50)

In summary, the dissipation of cadmium via phosphate fertilizers is large, and is growing at a rate which would double the Fulkerson estimate before 1980. Since phosphoric acid is the precursor for most phosphate fertilizers, any control options aimed at removing the cadmium from fertilizers would logically be applied to the phosphoric acid manufacturing segment. The technology for removing cadmium is not apparent, and it is recommended that research be aimed at this objective.

Another control option is the regulation of the cadmium content of sulfuric acid that is used for phosphoric acid manufacture, with the objective of preventing the use of smelter by-product sulfuric acid for this purpose.

Wet-process phosphoric acid is also used in the manufacture of calcium phosphates for animal feeds. The potential for cadmium entering the food chain in this manner should be investigated.

Coal

The Fulkerson(1) estimate for cadmium in coal was based upon an annual consumption of 450 million metric tons (500 million short tons); and upon a cadmium content in coal of 0.25 to 2.0 ppm. These data resulted in a cadmium quantity associated with coal of 110 to 900 kkg per year. At a representative single value of 1 ppm, the annual quantity of cadmium is 450 kkg.

Because of the uncertain fate of the cadmium, Fulkerson did not apply a factor for air pollution abatement. Klein and Russell,(97) based upon the work of Billings and Matson,(106) used a 90 per cent collection efficiency for cadmium (and for other metals in coal except mercury) for a power generation station's electrostatic precipitator. Yost(4) measured an emission rate for cadmium in the stack gas of a coal-burning power plant (downstream from an electrostatic precipitator) of 0.324 mg/sec. With an assumed coal consumption rate of 1.7 kg/sec (commeasurate with a reported steam generation rate of 13.9 kg/sec), the cadmium emission rate was 0.19 mg per kg of coal burned; compared to a representative value of cadmium in coal of 1 mg/kg. The primary zinc industry(5) achieves 95+ per cent collection efficiency for cadmium in electrostatic precipitators and baghouses. In comparison, Yost's data for a municipal refuse incinerator with a wet scrubbing-system resulting in less than one per cent collection efficiency for cadmium.(4)

Based upon these observations, a cadmium collection efficiency of 85 per cent has been assumed for present-day coal-burning electric power stations, generally equipped with electrostatic precipitators. Since about 97 per cent of all the coal is burned in such facilities, and 3 per cent is burned in residential or commercial furnaces with no air pollution control, then the overall distribution of the cadmium will be:

Air Emissions,	17.5 per cent or 80 kkg/yr
Residues and Captured Fly Ash,	82.5 per cent or 370 kkg/yr

The cadmium in the fly ash will, in general, be partially accessible to the environment via dusting and via leaching.

Of major importance in this estimate of cadmium emissions from coal is the projected increases in coal utilization due to the energy situation. Table 23 lists the rather stable coal statistics for the past five years, but the 1980 projection reflects an annual growth rate of over 6 per cent. The impact is that the domestic consumption in 1980 is expected to be around 760 million metric tons, 70 per cent higher than the base for the Fulkerson estimate. Hence, the cadmium quantity could be increased to around 760 kkg per year by 1980.

The data of Table 23 also show that in 1974, 72 per cent of the total coal consumed was for electric power generation. Of the remainder, 17 per cent was consumed by coke plants, 11 per cent by other manufacturing and mining industries, and only 1 per cent was delivered by retail dealers.(15) The proportion for electric utilities is expected to increase by 1980.

Much research is currently underway in developing coal conversion processes (synthetic oil and synthetic low-and-high-Btu gas). The EPA is actively investigating the fate of the heavy metals in these conversion processes. In one preliminary study(51) of a high-Btu gasification process, starting with Pittsburgh No. 8 coal containing 0.78 ppm of cadmium, 24 per cent of the cadmium was volatilized in the first stage (430°C and 1 atmosphere), an additional 23 per cent in the second stage (650°C and 74 atmospheres), and an additional 15 per cent in the third stage (1000°C and 74 atmospheres), leaving 38 per cent of the original cadmium in the residue. As expected, the more volatile trace elements (Cd, Hg, Pb, As, Se) wound up primarily in the product gas, while most of the less volatile trace elements (Cr, Ni, and V) remained primarily in the residues.

The research emphasis on removal of trace elements from synthetic gas and oil, plus the regulatory emphasis on air pollution abatement from power generation stations and other stationary sources, should result in proportionately less cadmium being emitted to the air from coal (or coal products) combustion. If a 95 per cent overall capture efficiency is projected for 1980, the air emissions of cadmium would be 80 kkg per year (about what they were in the 1970 time period), while the captured fly ash and residues would contain 680 kkg per year of cadmium.

The growth of coal consumption is expected to continue well past 1980; the U.S. recoverable reserves are estimated to be 394 billion metric tons.

TABLE 23

U.S. BITUMINOUS COAL STATISTICS (MILLION METRIC TONS/YEAR)
SOURCE: BUREAU OF MINES (15)

Year	Production	Exports	U.S. Consumption (total)	U.S. Consumption (electric power)
1970	547	64	468	290
1971	501	51	449	299
1972	540	51	469	317
1973	537	48	505	351
1974	535	55	490	355
1980*	812	(54)	(758)	580

*Projection

The control options suggested are:

1. Continued stringent air pollution controls, especially for coal-burning electric power generation stations.
2. Research emphasis upon removal of the cadmium from synthetic oil or gas prior to combustion.
3. Research and regulation on the disposal of residues and of collected fly ash in environmentally-adequate ways.

SECTION X

CADMIUM TOXICITY

Although a deadly poison in high concentrations, cadmium levels necessary to cause acute toxic episodes have not been found environmentally in the United States except in isolated cases of occupational exposure. Chronic cadmium poisoning has occurred as a result of occupational exposure, and, in Japan, as a result of environmental sources. Table 24 provides a summary of the acute toxic dosages in a variety of animal species for cadmium and several of its salts.(52) In man, critical threshold levels for observed effects is about 200 ppm of cadmium in the renal cortex.(53)

Chronic studies have been performed by a number of investigators. Cadmium stearate fed orally to rats for 90 days caused decrease in growth and histopathologic changes of the stomach, intestines and testicles.(54) Ingestion of 5 ppm of cadmium with drinking water by mice resulted in tissue concentrations comparable to that seen in man, with increased male mortality.(54) At 10 ppm in rats for 60 days, cadmium inhibits the following enzyme systems: oxidative phosphorylation, phosphatase and succinic oxidase.(55) In rabbits, cadmium can evoke hypocalcemia.

The effects of cadmium on the immune response have not been resolved. Studies in rats show that a dose of 0.6 mg/kg at 14 and 7 days prior to antigen injection, cadmium respectively enhanced and suppressed antibody synthesis.(57) In vitro, cadmium cytophagic effects on erythrocytes and platelets is similar to that seen with other heavy metals and is attributed to a toxic effect on sulfhydryl enzymes.(58) Thus the anemia is manifested, and cadmium has been shown to be transported to bone marrow where it inhibits hemoglobin synthesis by being incorporated into the molecule.(59) Cadmium does not exert any observable mutagenic effects or chromosome abnormalities.(60) Although it readily crosses the placenta no teratogenic changes have been manifested.

TABLE 24

ACUTE TOXICITY OF CADMIUM AND ITS SALTS

Product	Species	Route	Toxic Dose	
Cadmium (fumes)	human	inhalation	TCLo	9 mg/M
	rat	intramuscular	TDLo	700 mg/kg
Cadmium Chloride	rat	oral	LD50	88 mg/kg
		s.c.	TDLo	2.2 mg/kg
		i.v.	LD50	4.48 mg/kg
	dog	inhalation	LCLo	320 mg/M
Cadmium Fluoborate	rat	oral	LDLo	250 mg/kg
Cadmium Fluoride	guinea pig	oral	LD50	150 mg/kg
		s.c.	LDLo	200 mg/kg
Cadmium Fluosilicate	rat	oral	LDLo	100 mg/kg
	mouse	inhalation	LCLo	670 mg/M
Cadmium Lactate	Mouse	s.c.	LD50	13.9 mg/kg
Cadmium Oxide	rat	oral	LD50	72 mg/kg
		inhalation	LC50	500 mg/M
		s.c.	TDLo	12 mg/kg
Cadmium Phosphate	Mouse	inhalation	LCLo	650 mg/M
Cadmium Stearate	rat	oral	LD50	1225 mg/kg
		intravenous	LD50	9.31 mg/kg
		i.p.	LD50	11.38 mg/kg
Cadmium Succinate	rat	oral	LD50	660 mg/kg
Cadmium Sulfate	rat	s.c.	TDLo	22mg/kg/10WI
	dog	s.c.	LD50	27 mg/kg
Cadmium Sulfate Tetrahydrate	rat	s.c.	TDLo	8mg(Cd)/kg/10WI
Cadmium Sulfide	rat	s.c.	TDLo	110mg/kg

ABBREVIATIONS

TCLo	Lowest toxic concentration evoking an adverse response
TDLo	Lowest toxic dosage evoking an adverse response
LD50	The dose causing death in 50% of the animal population
LCLo	Lowest lethal concentration
LDLo	Lowest lethal dose
LC50	The concentraction causing death in 50% of the animal population
10WI	10 weeks of dosing at a specified intermittent interval
s.c.	subcutaneous
i.v.	intravenous
i.p.	intraperitoneal

Although injections of cadmium chloride into male rats resulted in pleomorphic sarcomas at the injection site 10 to 16 months later, probably as a result of injury to tissues of mesenchymal-mesodermal origin,(61) this response is not indicative of a carcinogenic effect since many substances, when similarly administered to rats, induce the same changes. Rather, it is a local response to tissue (fibroblast) injury. Cadmium has not been implicated in lung cancer in animals or man.(62) Analysis of zinc and cadmium levels in patients who died of emphysema, bronchitis and pulmonary cancer and emphysema in comparison to levels in patients who had only lung cancer or who died with no renal, hepatic or lung involvements indicated that there was no specificity for cadmium in primary tumors.(63) However, one group of investigators(64) showed a correlation between air pollution and increased incidence of prostatic cancer in white males in Nashville, Tenn. Since cadmium oxide dust is known to be present in the air they inferred a possible causal relationship but offered no definitive proof.

Exposure of rats to an aerosol of cadmium chloride solution for 1 hour on 5, 10 or 15 occasions resulted in acute vascular congestion and alveolar hemorrhage followed by polymorphonuclear cell infiltration. Localized granulation tissue subsequently developed about the bronchioles. By the 10th day after exposure, the granulation tissue had undergone change to fine scar tissue with destruction of adjacent alveoli, resembling human centrilobular emphysema. Cadmium content of lungs was proportional to the number of exposures. It has been previously shown that renal and liver levels of cadmium increase with chronic obstructive lung disease and body burden is well correlated with the number of pack-years of cigarettes smoked.(65) These changes cause a decrease in lung compliance and dyspnea.(66) The mechanism of the cadmium toxicity may involve inhibition of Na^+, K^+, Mg^{++} ATPase systems of pulmonary alveolar macrophages and cellular membranes.(67)

0.5 mg per kg, s.c., of cadmium chloride or stearate causes glycosuria and proteinuria in mice.(67) 0.25 mg per kg, s.c., to rabbits also resulted in nephropathy with alterations of proximal tubules and mild glomerular changes.(68) The proteinuria was characterized by a low albumin level and fairly high alpha and beta fractions, and a distinct fraction in the anterior gamma region. A basic protein in the renal cortex migrated as muramidase.(69)

Comparisons were made of urine protein levels in normal and 40 cadmium exposed workers.(70) Normal levels of excretion were 50 mg per day, while the cadmium exposed workers excreted between 80 and 2600 mg per day. Subjects with greater than 150 mg per day proteinuria showed electrophoretic patterns with low albumin, high alpha-2, beta and gamma-globulins. Proteinuria of greater than 400 mg per day also yielded a distinct beta peak. There was little variation in the electrophoretic patterns noted at 6 month intervals. The proteinuria had a high mucoid content. Battery workers with 10 years exposure to cadmium showed anosmia and proteinuria but no correlation to other disease states.(71)

Metallothioneins are low molecular weight proteins found in a variety of tissues and are responsible for the transport of a variety of metals within the body. The accumulation of cadmium in the kidney and liver is dependent on the storage of cadmium in the metallothionein. This protein readily passes through the glomeruli and can subsequently be found in urine. As a result of the concentrating activity of cadmium in the kidneys, cadmium will evoke renal tubular dysfunction when threshold limits are exceeded.

Rats given 5 mcg per ml of cadmium in drinking water from time of weaning began to develop hypertension after about 1 year. This increased in incidence with age and females were affected more than males, but mortality was greater in males. There is a correlation between cardiovascular death rates and cadmium present in air as an industrial pollutant as well as hypertension and water softness due to cadmium. Atherosclerosis is also associated with water softness as well.(72)

Cadmium produces persistent hypertension in rabbits and dogs. It is predominately deposited in the kidney and liver and to a lesser extent in the blood vessels of cadmium hypertensive rabbits. Cadmium was capable of inhibiting vasopressor induced renal vasoconstriction.(73)

Some epidemiologic studies have been carried out in the U.S. In a survey of 77 midwestern cities, no correlation was found between cadmium in air fallout and cardiovascular disease.(74) However there appeared to be a simple correlation between cadmium content of milk and cardiovascular disease in 59 U.S. cities.(75) Cadmium concentration in air was correlated with deaths from heart disease and arteriosclerotic heart disease in 28 cities (R = 0.76). Zinc, with which cadmium is often associated, also had a good correlation (R = 0.56). Patients with increased blood pressure have increased cadmium levels in renal tissue. This may contribute to the pathophysiology of cardiovascular disease.(76)

Studies have indicated that cadmium oxide is more toxic than cadmium dust or other cadmium salts. Threshold limits have been established at 0.1 mg of cadmium oxide per m^3 of air. Table 25 compares the toxicological effects of cadmium poisoning in experimental animals and in man.

In man the most common symptoms of acute cadmium poisoning are xerostomia, vomiting, headache, cough, chest pain, and anorexia. High concentrations may result in severe respiratory difficulty and unconsciousness followed by bronchopneumonia and even death. Chronic exposure to low levels of cadmium can result in the following symptoms: fatigue, nervousness, cough, shortness of breath and gastric disturbance, impairment of sense of smell, kidney function and pulmonary function - often leading to emphysema. Often a yellow ring forms on the teeth of workers.(77)

In chronic cadmium poisoning the typical systems present are shortness of breath due to emphysema with urinary excretion of a characteristic low molecular weight protein. The mortality rate resulting from the acute pneumonitis is about 15-20%, and this acute toxicity has no resemblance to the chronic form of the disease.(78)

TABLE 25

COMPARISON OF TOXICOLOGICAL EFFECTS OF CADMIUM IN ANIMALS AND MAN

ANIMALS

Amyloidosis
Anemia
Cancer (?)
Cirrhosis
Dental Changes
Enteritis
Gastritis
Hypertension
Hypocalcemia

Shortened life-span
Nerve damage
Ovarian Changes
Pancreatic atrophy
Proteinuria
Pulmonary emphysema
Renal Damage
Testicular atrophy and lesions
Possible teratology
Toxemia of pregnancy
Weight Loss

MAN

Aminoaciduria
Aneuria
Anosmia
Osteoporosis
Dental Changes
Gastritis
Glucosuria
Hypercalciuria
Increased erythrocyte sedimentation rate
Liver damage
Proteinuria
Pulmonary emphysema
Reduced working capacity
Renal damage
Renal stones

Kidney biopsies of cadmium poisoned individuals showed thickening of the small arteries and a slight degeneration of the tubules while pulmonary function tests showed constrictive ventilatory impairment. Proteinuria and glycosuria were predominate findings.(79)

One group of investigators(80) could not show any correlation between chronic cadmium exposure and hypertension, cardiovascular disease or hypercholesterolemia.

Itai-Itai disease involves renal tubular dysfunction accompanied by osteomalacia and osteoporosis. Its symptoms include:

- severe pain at regions of groin, loins, back and joints,
- duck gait
- a tendency to fracture of bones
- proteinuria and glycosuria
- an increase in serum alkaline phosphatase and a decrease in serum inorganic phosphorous.

Most victims are women who have borne several children and are now menopausal. Itai-Itai disease occurs in Japan in the Jintsu River Basin and is the result of chronic cadmium poisoning resulting from a daily diet contaminated by cadmium released through mining activities.(81) Research studies showed that the chronic poisoning leading to this condition occurred because of such factors as pregnancy, lactation, aging and calcium deficiency.

Whole body retention studies were carried out in rats using 4 routes of administration. The following results were obtained:(82)

Route of Administration	Per Cent Absorption
intraperitoneal	93
intravenous	91
inhalation	41
oral	2.3

Immediately after inhalation, 9.7% of total inhaled cadmium was the lungs. The route of administration did not influence the rate of elimination or the biological half-life. In female monkeys, within 5 days of administering 1 mcg of cadmium, 43.5% was excreted, 46.8% remained in the gastrointestinal tract, 7.21% was in the walls of the gastrointestinal tract and 0.65% was distributed in the body. Maximum absorption was 1.3%.(83) In mice, maximum absorption increases acutely with increased dose, but in chronic exposure absorption decreases as tolerance develops. Following oral dosage to mice, 50 - 70% is absorbed from the gastrointestinal tract and 50 - 60% of this level was excreted by the kidneys on the first day. The remainder was stored primarily in the liver and kidney.(84) Intestinal absorption in mice was shown to be 2 - 3%(85) with a half life of 50 days. A 55 year old man has an absorption rate of 5.34%. The accumulation of cadmium reaches a ceiling level after about 30 years of age.

The data below are from a number of studies of cadmium levels in human tissue:

Blood	0.2 mcg/100 ml
Blood	0.7 mcg/100 ml
Urine	0.82 mcg/liter
Urine	1.15 mcg/liter
Hair	0.7 ppm
Kidney	$> 10^4$ mcg/gm (ash weight)
Kidney	55 mcg/gm (wet weight)
Kidney	upper limit of 5000 mcg/gm (ash weight)
Fetal tissue, first trimester	0.032-0.07 mcg/gm (wet weight)
Fetal tissue, second trimester:	
Liver	0.113 mcg/gm (wet weight)
Kidney	0.05 mcg/gm (wet weight)
Brain	0.140 mcg/gm (wet weight)

Liver/kidney ratios of cadmium in various Japanese populations are given below:

Type Individual	Ratio
Normal	0.10 to 0.20
Exposed	> 0.35
Itai-Itai Disease	1.4 to 3.7
Residents of Cadmium Polluted Areas	0.05 to 1.25

Two studies have been carried out in the United States and have shown a mean weighted average of 16 ppm of cadmium in renal tissue. In studies where disease victims and smokers were not excluded from the tabulation, mean renal levels of 50 and 25 ppm have been reported.(53,67) No studies of cadmium concentration on the existence of renal tubular dysfunction have been made of environmentally exposed populations in the United States. No correlations have been made between renal cadmium levels and hypertension. But there appears to be a correlation between neoplasia and renal cadmium content, though it is not a cause and effect relationship.(86)

In summary, cadmium is highly toxic with a rating of 5 on a scale of 1 to 6. The acute lethal dose by ingestion is estimated to be between 5 and 50 mg per kg or between 0.35 and 3.5 g for a 150 pound man. The maximum permissible level in drinking water is 0.01 ppm. This standard (U.S. Public Health Service) is based on a tenfold reduction of the lowest tested level (0.1 ppm) that results in cadmium accumulation in rat kidneys. The following illustrates the toxicity scale for ingested cadmium:

Level (mg)	Response
3 to 90	emetic threshold, non-fatal incidents
15	experimentally induced vomiting
10 to 326	reported severe but non-fatal toxic symptoms
350 to 3500	estimated lethal dose
8900	reported lethal dose

By inhalation cadmium has a toxicity rating of 6. The recommended maximum atmospheric concentration of cadmium fumes is 0.1 mg per cubic meter of air for an 8 hour period. The inhalation of 40 mg of cadmium with pulmonary retention of 4 mg is considered fatal to man.

Aside from Itai-Itai Disease, which occurs in only one section of Japan and only amongst menopausal women, cadmium has not been associated definitively with other specific disease states - particularly in the United States. However, that is not to say that cadmium is non-toxic. On the basis of extensive reviews carried out by Friberg et.al.(81) the following conclusions may be made:

1. Cadmium can be a very serious health problem in industrial settings and in the general environment. Environmental contamination is particularly serious since the metal accumulates in the body during long-term exposure.
2. Prolonged exposure to cadmium dust can cause emphysema in industrial workers, and some evidence exists that persons in the general population who have chronic bronchitis and emphysema have larger-than-normal body burdens of cadmium, although a definite cause-and-effect relationship has not been established.
3. The internal organs affected most critically by cadmium are the kidneys. Damage to the tubules produces excessive proteinuria. Extensive damage causes acute secondary defects including osteomalacia, the softening of the bones that characterizes Itai-Itai disease.
4. Experimental and autopsy findings demonstrate that serious kidney impairment has already occurred if concentration of cadmium in the kidney cortex reaches 200 ppm.
5. Hypertension has developed in some experimental animals after prolonged exposure to cadmium. No conclusive evidence exists that cardiovascular disease in human beings is caused by cadmium exposure but epidemiological studies statistically

linking the two merit further investigation. Other internal diseases caused by excessive exposure include anemia and liver damage.

6. Research is needed on concentrations of the metal in body organs other than the kidney, such as the liver, pancreas, and thyroid gland. Additional studies should be carried out regarding the carcinogenic, teratogenic and mutagenic effects of cadmium.

SECTION XI

ASSESSMENT OF HEALTH HAZARDS

The most direct way of assessing the chronic health hazards presented by cadmium is to compare the measured 50-year level of accumulated cadmium in the renal cortex (presently estimated at 16 to 50 ppm) with the threshold level for renal dysfunction (200 ppm). This comparison results in a "safety factor" of between 4 and 12.5, which has caused a large measure of concern because it is not a comfortable margin of many orders of magnitude. Other reasons for concern include the Japanese public health problem (in the Jintsu River Basin) of environmentally-caused cadmium poisoning, which emphasizes the narrow safety factor; the rather large changes in cadmium release to the environment (as discussed in Sections IV through IX); and the built-in lag between a long-term buildup of cadmium in the human body and the emergence of disease symptoms.

The very recent few years has produced both mounting concern and considerable progress towards understanding; both the result of the development of refined atomic absorption spectrophotometric procedures which permit the determination of cadmium at concentration levels common in the biosphere.

One key question which has received much attention is whether the cadmium being released to the environment as the result of man's activities is finding its way into the food chain, or, instead, being assimilated by natural sinks such as the soil and the oceans. Some of the more recent work is discussed below.

Another key subject is the relationship of daily cadmium intake levels (which can be monitored) to the long-term accumulation in the renal cortex (which cannot be continuously monitored). The objective is to determine the "safety factor" in terms of current average daily intake, which is estimated as 75 ± 25 micrograms, as compared to the critical daily intake (associated with the critical 50-year accumulation of 200 ppm in the renal cortex). This subject is also discussed below.

However, the definitive and quantitative assessment of the health hazard is still not available. Some observors at one extreme doubt whether the long-term accumulations in man are any different from what they always have been, since cadmium is a widely-dissipated element in natural soils and waters, and so they see no cause for alarm or for regulation of cadmium emissions. Some observers at the other extreme advocate the fail-safe course in dealing with a toxic material which may only show health effects after many years of exposure; they would strictly regulate cadmium emissions without a definitive cause-and-effect relationship.

Observers at both extremes agree to actively seek definitive answers and to carefully monitor the situation (now that the analytical tools are available). In the interim, a middle-of-the road approach seems to be that recommended in 1972 by the Joint FAO/WHO Expert Committee on Food Additives(87) to not permit any increase in the present daily intake level:

> "In view of the critical level (of cadmium in wet renal cortex) of 200 mg/kg, the Committee feels that present day levels of cadmium in the kidney should not be allowed to rise further. If the total intake of cadmium does not exceed 1 μg/kg body weight per day, it is unlikely that the levels of cadmium in the renal cortex will exceed 50 mg/kg, assuming an absorption rate of 5 per cent and a daily excretion of only 0.005 per cent of the body load (reflecting the long half-life of cadmium in the body). The Committee therefore proposes a provisional tolerable weekly intake of 400-500 μg per individual. However, because of the many uncertainties involved, this estimate should be revised when more precise data and better evidence become available.
>
> "At the present time the cadmium intake of many populations is unknown and analytical methods, although

adequate, require further standardization. There are uncertainties regarding the absorption and excretion of cadmium in various nutritional and metabolic states, and it is not known whether populations with excessive cadmium loads derived from the diet have developed proteinuria.

"Such diet surveys as have been performed indicate that in some areas cadmium levels approach or even exceed the values recommended above, because of environmental pollution. At present, cadmium inhaled from the urban atmosphere does not contribute a significant proportion to the total body burden. However, significant absorption through heavy smoking is possible. The continuing contamination of the environment from industrial and other sources is likely to increase the cadmium concentration in food, and in the future this may lead to hazardous levels. The Committee recommends that every effort should be made to limit, and even reduce, the existing pollution of the environment with cadmium."

Cadmium Transport in the Food Chain

A number of papers have recently shed light on the relationship between cadmium pollution and the appearance of higher-than-normal levels of cadmium in soils and plants. The sources of cadmium pollution have included generally-industrialized urban areas,(4,92) coal-burning power plants,(97) zinc smelters,(87,90,91) and heavily-travelled roads.(45,92) The addition to soil of cadmium-rich phosphate fertilizers and sewage sludge(4,93,94,95,96) has been studied, and investigators have determined the plant take up resulting from delibrate doses of cadmium to the soil.(89,90,98) Relevant data is also available from the Jintsu River Basin in Japan.(87) The transport of cadmium to land animals and to aquatic organisms has also been investigated.(4,88)

The cadmium content of natural (unpolluted) soils is reported to be generally less than 1 ppm,(53) with one "common" level of 0.06 ppm,(93) an "average" level of 0.88 ppm(90) in certain Canadian agricultural soils, an "average" level of 0.04 ppm(4) in certain U.S. (mid-west) agricultural soils, and an overall crustal abundance of 0.15 ppm.(1) In comparison, the cadmium content of common foodstuffs in the U.S., listed in Table 26, is generally below 0.10 ppm, but values in selected foods (not known to be contaminated) have been higher.(87)

The uptake of soil cadmium by plants is dependent upon a great number of factors, particularly soil type and organic content, pH, and plant species. Cadmium in soils seems to be tightly bound and not readily removed by leaching; it may be adsorbed on aluminum oxide or iron oxide and it may be complexed by organic materials of low solubility. Sediments in rivers and lakes have been shown to accumulate cadmium (as has sewage sludge) from waters.

Despite the above mechanisms for binding cadmium, the recent evidence accumulated by the investigators (listed above) of plant uptake is conclusive in that plants will reflect higher-than-normal cadmium levels in soil over the entire range of cadmium concentrations. Prior to 1970, the evidence was inconclusive for plant uptake at cadmium concentrations in the soil in the 0.1 to 50 ppm range; but positive evidence has since been reported. Representative experimental results of recent work is listed in Table 27.

The impact of this evidence is that cadmium contamination of soil (in the concentration ranges observed in the vicinity of smelters, power plants, and roads, and resulting from the application of fertilizer and sludge) does result in comparable cadmium contamination of the food chain.

Relationship Between Intake and Accumulation

The modeling of the human intake-retention-excretion balance for cadmium has been sought over the past few years, so as to relate daily

TABLE 26

CADMIUM IN FOODS
SOURCE: OECD(87)

Food	Max. Cadmium Conc. (mg/kg wet weight)	
	1968-1969	1969-1970
A. Composite Classes (USA survey)		
Dairy products	0.09(10)[a]	0.01(9)
Meat, fish, poultry	0.06(21)	0.03(22)
Grain, cereal products	0.08(27)	0.06(27)
Leafy vegetables	0.08(27)	0.14(28)
Legume vegetables	0.03(16)	0.04(10)
Root vegetables	0.08(24)	0.08(27)
Garden fruits	0.07(25)	0.07(27)
Fruits	0.38(15)	0.07(10)
Oils, fats, etc.	0.13(27)	0.04(28)
Sugar and adjuncts	0.07(18)	0.04(27)
Beverages	0.04(8)	0.04(9)
Potatoes	-	0.08(29)
B. Some Extreme Individual Measurements		
Olive oil (Spanish)	1.22	
Ementhaler cheese	1.48	
Cod Liver oil	1.71	
Tea (Japanese) green leaves	2.50	
Oysters, fresh	3.66	
Anchovies, canned	5.39	
Beef kidney (F.R.G.)	12.00	

a = Samples were taken from 30 markets in 24 different U.S. cities. The number in brackets is the number of samples whose measured cadmium concentration was above 0.01 mg/kg (max. 30).

TABLE 27

PLANT UPTAKE OF CADMIUM FROM SOILS

Investigator	Plant	Cd in Soil, ppm	Cd in Plant, ppm
Haghiri(98)	Soybean Tops ↓	2.5 5 10 15 20 30 40 50	7 10 13 14 18 20 23 24
Haghiri(98) ↓	Wheat Tops ↓	2.5 5 10 15 20 30 40 50	3 5 8 9 10 12 14 16
John(90) ↓	Oat Shoots Oat Roots Oat Shoots Oat Roots	1.3 1.3 46.4 46.4	0.51 1.11 16.1 36.3
Lagerwerff(45) ↓	Grass ↓	0.22 0.40 1.45	0.50 0.73 0.95
Lagerwerff(99) ↓	Radish Roots ↓	0.11 0.34 0.56	0.90 1.1 1.2

intake (a quantity which may be continuously monitored) with long-term accumulation in the renal cortex (a quantity which is a direct indicator of chronic cadmium poisoning, but which cannot be continuously monitored).

One such model[87] was constructed from the following arguments, each based upon experimental data:

1. Five per cent of ingested cadmium is absorbed into the bloodstream (inhalation of cadmium is neglected);
2. Cadmium accumulates in bodily organs from 90 per cent of the absorbed cadmium (assuming as experiments have shown, that about 10 per cent of absorbed cadmium is rapidly excreted);
3. The kidney, the critical organ from the point of view of the health effects of cadmium, contains one-third the body burden of cadmium;
4. The concentration of cadmium in renal cortex is one and a half times that in the kidney taken as a whole;
5. Well-established experimental data allow adjustment for the variation of kidney weight and food intake with age; and
6. Cadmium is excreted at the rate of 0.005 per cent (per day) of body burden, implying a whole-body half-life of 33 years.

The two questionable parameters in this model are the 5 per cent absorption rate and the 0.005 per cent excretion rate; the precision of the empirical evidence may allow a ±50 per cent variation in this 5 per cent absorption rate. The excretion rate was apparently adjusted so that the model, with appropriate time functions for kidney weight and food intake, resulted in a 50-year renal cortex cadmium concentration of 50 ppm for an adult daily cadmium intake rate of 62 micrograms. Assuming the form of the model is appropriate, a much higher excretion rate would be needed to match another set of reported data, a 50-year renal cortex concentration of 16 ppm for a daily intake rate of 75 ± 25 micrograms.

Without further refinement of the model, values for a critical daily intake rate (corresponding to the threshold renal cortex concentration of 200 ppm) may be anywhere between 200 and 1,000; implying a "safety factor" of between 3 and 13.

The key result of this exercise is not that the "safety factor" on daily intake may be as low as 3 (which would imply a near-panic situation); but that the safety factor probably is no larger than 13. This implies a situation of caution and careful monitoring, especially in light of the recent evidence that cadmium can be transported into the food chain from contaminated soil on an approximately one-to-one concentration basis.

The total agricultural land, of course, is a vast sink for the assimilation of cadmium, assuming the cadmium contamination is distributed evenly. At a "natural" cadmium concentration in soil of 0.15 ppm, the topmost meter of the continental lithosphere contains approximately 100 million metric tons of cadmium.(1) The instance of Itai-Itai disease in the Jintsu River Basin of Japan could be cited as an example where a large quantity of cadmium contamination was not distributed over a large agricultural area and where the inhabitants did not balance their home-grown food with "imported" food. In this instance, the Jintsu Valley was close to a closed ecology; the consumption ratio of locally-grown foods to "imported" foods ranged from 0.7 up to 2.4.(87)

To a great extent, the United States represents the reverse situation, where foodstuffs are widely disseminated across the country for consumption. Moreover, the U.S. population is much more mobile, so that the chances are smaller for very locally-high levels of cadmium being a continuing factor over a 50-year period.

The other side of the argument, however, has merit as well. There is a significant proportion of the U.S. population which is not mobile, and which might live for many years in the cadmium shadow of an industrialized area, a coal-burning power plant, a municipal incinerator, a steel plant, a zinc smelter, or a heavily-travelled roadway. Some of these individuals may eat a larger-than-average proportion of home-grown food (i.e., backyard vegetable gardens, home canners, etc.) or of bioconcentrating seafood. The accumulation of cadmium in some individuals may be promoted by heavy smoking or by occupational factors, or by variations from average intake/absorption/excretion rates.

Further research to relate intake to accumulation is quite clearly needed. At this point, arguments made above (on both sides of the question) are highly qualitative. While the sensitive analytical tools for measuring and monitoring cadmium levels in the environment have been developed, the means for quantitatively assessing the hazards associated with these levels have not as yet been developed.

SECTION XII

QUANTITIES OF CADMIUM RELEASED TO THE ENVIRONMENT

Fulkerson and Goeller(1) compiled an estimate, by source, of the annual quantities of cadmium entering the environment in 1968. This estimate is reproduced as Table 28. The total emissions to air, water and soil were estimated as 2,500 to 3,600 metric tons per year (as elemental cadmium). In the time since that estimate was made, additional data has become available, and some of the production, use, and emission patterns have significantly changed. Previous sections of this report have discussed these later data and changes in detail; the revisions and additions are summarized below.

Zinc Ore Mining and Beneficiation

The total cadmium in domestic mine tailings is estimated at 250 kkg per year. Little or no waterborne cadmium is assumed to result from adequate water reuse and containment pond technology.

Zinc Recovery from Ore Concentrates

The cadmium emissions to the air (based upon 95 per cent collection efficiencies) are estimated as follows:

Roasting	~0
Sintering	100 kkg/year
Horizontal Retort	0.3 kkg/year
Vertical or Electrothermal Retort	2.0 kkg/year
Electrolytic Plants	~0
Total	102 kkg/year

The total estimate is only one-tenth the previous estimate, and reflects the closing of many older plants (especially pyrometallurgical plants) and the addition of efficient dust collection equipment.

TABLE 28

FULKERSON-GOELLER EMISSION ESTIMATES (1968) FOR U.S.
UNITS: METRIC TONS PER YEAR AS ELEMENTAL CADMIUM

Source	Air Emissions	Soil and Water Emissions
Zinc Ore Mining & Beneficiation	0.2	181
Primary Zinc Industry	953	294
Electroplating Shops	~0	?
Pigment Manufacture	9.5	
Stabilizer Manufacture	2.7	
Alloy Manufacture	2.3	
Battery Manufacture (& Misc.)	0.7	0.2
Iron and Steel Industry	<100	<900
Incineration	86	
Rubber Tire Wear	5.2	
Phosphate Fertilizers	?	23-230
Coal Combustion	113-907	
Diesel & Fuel Oil Combustion	18-90	
Lubricating Oils	0.8	
Sewage Sludge Disposal		22-57

Cadmium as waterborne effluents is estimated as:

1971 -72	10 kkg/year
1977	2.0 kkg/year
1983	1.3 kkg/year

The significant decrease is the result of water pollution abatement practices. The prior estimate of 294 kkg/year is of questionable validity, since it was derived by difference (and not by direct measurement).

Electroplating Shops

No previous estimate was made for the water and land emissions from this industry. The estimates in this study are:

	1972	1977	1983
Waterborne Wastes, kkg/year	10.5	4.0	0
Waste to Land Disposal, kkg/year	73.5	80	0

This industry exemplifies the results of pollution abatement practices.

Pigment Manufacture

The 1974 emissions (as elemental cadmium) are estimated as:

Waterborne effluents,	0.75 kkg/year
Land-destined wastes,	16.5 kkg/year

Battery Manufacture

The waterborne effluents are estimated to contain 0.3 kkg/year of cadmium. The land-destined wastes are estimated to contain the following quantities of elemental cadmium:

1973,	8.4 kkg/year
1977,	11.4 kkg/year
1983,	9.1 kkg/year

Secondary Non-Ferrous Metals Industry

The emissions of cadmium to the air are estimated to be less than 2.2 kkg/year.

Iron and Steel Industry

The emissions of cadmium to the air are estimated to be 10.5 kkg/year. The collected dusts, destined for land disposal, are estimated to contain 330 kkg/year of cadmium.

These estimates, much lower than the prior estimates, are based upon data specific to the scrap grades used in steel-making. The results of effective air pollution abatement practices are also reflected in the new estimate.

Galvanized Products

The release of cadmium to the environment via the corrosion of galvanized products was very crudely estimated to be 40 kkg/year.

Phosphate Fertilizers

The quantity of cadmium applied to the land via phosphate fertilizers is projected to be 100 kkg/year in 1975 and 130 kkg/year in 1980. A continued annual growth rate of 5 to 7 per cent is estimated.

Coal Combustion

The estimate of cadmium release via coal combustion is:

	1974	1980
Air Emissions, kkg/year	80	80
Land-Destined Wastes, kkg/year	370	680

The increase in land-destined wastes reflects a large growth rate in coal utilization for electric power generation; the air emissions are stable reflecting very stringent controls for new power stations and more stringent controls retrofitted to existing power stations (to increase the overall cadmium collection efficiency from 85 per cent in 1974 to 90 per cent in 1980).

Sewage Sludge

The Fulkerson-Goeller estimate in Table 23 was based upon a per capita dry sludge solids quantity of 0.091 kilograms per day for 120 million (out of 200 million) people; and upon an average cadmium content of dry sludge solids of 15.6 ppm (which was derived from Swedish data).

In the 1971 and 1973 time period, a review of about 100 literature references, and analysis of 80 additional sludge samples collected from United States sewage treatment plants, were conducted by the Environmental Protection Agency's National Environmental Research Center in Cincinnati.(96) The statistical distribution of heavy metal values tended to be log-normal, with a few very high values that could ordinarily be traced to specific industrial discharges. For cadmium, the results from the literature were a geometric mean of 61 ppm, with a spread (the antilog of the standard deviation of the log-normal distribution) of 5.89; and a geometric mean of 93 ppm for the atomic absorption determinations for the sludge samples. Using an intermediate value of 75 ppm for cadmium, the quantity of cadmium in sewage sludge becomes 300 metric tons per year.

The source of such a large quantity of cadmium could not be attributed to excretions of man. Using the values of Section XI (an average per capita daily intake of 75 micrograms and an excretion rate of 95 per cent), the cadmium excreted by 120 million people amounts to only 3 metric tons per year. Nor can this large quantity of cadmium in sewage sludge be primarily attributed to industrial effluents; it has been previously estimated that the primary zinc industry, the electroplating industry, and other industrial waterborne sources amount to perhaps 25 kkg per year of cadmium, only a fraction of which is discharged into municipal sewer systems. Although air emissions from all sources amount to about 300 kkg/year of cadmium, it is difficult to conceive of any large percentage of this quantity, once precipitated to the land, entering the municipal sewer systems via storm water into combined sewers or via inflow and infiltration. Rather, it appears reasonable that most of this airborne cadmium would either remain on the land or would run off directly into surface waters. Similarly, only a rather small fraction of the 100 kkg/year of cadmium in phosphate fertilizers could conceivably enter municipal sewer systems.

The cadmium impurity in phosphate detergents is a suspected source of the cadmium in sewage sludge. Using the impurity level of 16 ppm cadmium based upon P_2O_5 (the same as in phosphate fertilizers), the 1.1 million metric tons per year of sodium tripolyphosphate produced(49) would contain 10.2 metric tons per year of cadmium. Hence, the detergent contribution is also only a small fraction of the cadmium in sewage sludge.

Municipal sewage sludge (like river sediments and like other biological organisms) is an efficient collector of metals, including cadmium. As part of other research at a 28 mgd sewage treatment plant, Versar has determined that 85 per cent of the cadmium in the raw sewage is collected in the dewatered sludge. The average concentration of cadmium in the intake of community water supplies was measured to be 1.3 μg/liter,(26) and the quantity of municipal wastewater is approximately 200,000 liters per capita per year, or 24 x 10^{12} liters per year for 120 million people. Hence, the quantity of cadmium in municipal water intakes (which is collected in municipal sewage sludge) is approximately 31 metric tons.

The balance of the 300 kkg per year of cadmium in sewage sludge; less the human excretions (3 kkg/yr), industrial sources (25 kkg/yr), phosphate detergents (10 kkg/yr), and "natural" cadmium in water (31 kkg/yr); is about 230 kkg per year. A possible source for this balance is the cadmium in galvanized water and sewer pipes and in PVC sewer pipe. While the Brattleboro, Vermont, reservoir had only 2.1 ppb cadmium, the running tap water contained 8.3 ppb (cold) and 21.0 ppb (hot).(1) The Community Water Supply Survey, which collected 2,216 water samples at the consumer's tap in 969 water systems, resulted in an average cadmium concentration of 8 ppb in the 556 samples where the pH was between 7.0 and 7.4, but much less in other pH ranges.(26) By comparison, the 230 kkg/yr of cadmium unaccounted for in sewage sludge is equivalent to 9.6 ppb in sewage.

While galvanized pipe is suspect as the large source of cadmium in sewage sludge, the evidence is not conclusive. The quantity of zinc used for galvanizing tubes, pipe, fittings, tanks, and containers is approximately 72,500 metric tons per year;(14) at 0.035 per cent cadmium, the cadmium involved is only 25 kkg per year.

The total quantity of cadmium in sewage sludge, estimated as 300 kkg per year, is an increasing one for the following reasons:

1. The huge investment over the past few years in new, expanded, and upgraded sewage collection and treatment facilities is resulting in a commensurate increase in sludge quantities.
2. Recent restrictions on ocean dumping of sludge have increased the quantities intended for land disposal.
3. The increased cost of auxiliary fuels has influenced the choice of sludge incinerators for new facilities, increasing the quantities of sludge intended for land disposal.

Of the cadmium-containing sewage sludge, approximately 60 per cent is directly applied to land, 10 per cent is still ocean-dumped, and 30 per cent is incinerated. If the cadmium collection efficiency of sewage sludge incinerator scrubbers is 80 per cent, then the cadmium emitted to the air would be about 20 kkg per year, and the cadmium disposed of on land (including the sludge ash) would be about 250 kkg per year.

Municipal Incinerators

If an 80 per cent collection efficiency is applied to the previous estimate, then the cadmium emissions to the air from incinerators would be about 16 kkg per year, and the land-destined wastes would include about 70 kkg per year of cadmium.

Summary of Revised Estimates

Table 29 summarizes the revised emissions. The revised total release of cadmium to the environment is about 2,000 metric tons per year;

TABLE 29

REVISED CADMIUM EMISSION ESTIMATES

UNITS: METRIC TONS PER YEAR AS ELEMENTAL CADMIUM

Source	Airborne Emissions	Waterborne Effluents	Land-Destined Wastes	Total Emissions
Zinc Ore Mining & Beneficiation	0.2*	~0	250	
Primary Zinc Industry	102	10(1971-72) 2.0(1977) 1.3(1983)	~0	
Total: Extraction, Refining & Production	102	~7(1974-75) ~2(1980)	250	359(1974-75) 354(1980)
Electroplating Shops	~1	10.5(1972) 4.0(1977) 0(1983)	73.5(1972) 80(1977) 0(1983)	
Pigment Manufacture	9.5*	0.75	16.5	
Stabilizer Manufacture	2.7*	~0	~0	
Alloy Manufacture	2.3*	~0	~0	
Battery Manufacture	0.7*	0.3	8.4(1973) 11.4(1977) 9.1(1983)	
Total: Industrial Conversion	15	~8(1974-75) ~3(1980)	~102(1974-75) ~ 75(1980)	125(1974-75) 93(1980)
Secondary Non-Ferrous Metals	2.2	~0	20	
Iron and Steel Industry	10.5	~0	330	
Galvanized Products	~0	~0	40	
Rubber Tire Wear	5.2*	~0	~0	
Incineration	16	~0	70	
Total: Consumption & Disposal of Cd-containing products	34	~0	460	494
Phosphate Fertilizers	~0	~0	100(1975) 130(1980)	
Phosphate Detergents	~0	10.2	~0	
Coal Combustion	80(1974) 80(1980)	~0 ~0	370(1974) 680(1980)	
Diesel & Fuel Oil Combustion	50*	~0	~0	
Lubricating Oils	0.8*	~0	~0	
Sewage Sludge	20	~0	250	
Total: Inadvertent Sources	151	10	720(1974-75) 1,060(1980)	831(1974-75) 1,221(1980)
Grand Totals	300	25(1974-75) 15(1980)	1,500(1974-75) 1,800(1980)	1,800(1974-75) 2,100(1980)

*Estimates Unchanged from Fulkerson-Goeller Estimates.(1)

less than the previous estimate (Table 28) of 2,500 to 3,600 metric tons per year. The main reasons for this lower new value are:

1. Effective air and water pollution abatement by industry, prompted by the promulgation of specific guidelines and regulations by Federal and state governments.
2. The contraction of the zinc industry, and particularly the closing of older pyrometallurgical smelters.
3. New calculations of emissions, particularily for the steel industry and for the zinc industry.

The totals of Table 29 show that the waterborne cadmium effluents from industry are close to and approaching a comparatively negligible quantity. The reasons are that wastewater treatment technology for cadmium removal is well established and is effective; that Federal legislation for controlling waterborne pollution is far-reaching and effective; and that the analytical technique for monitoring cadmium in effluents is well-developed and in wide use.

The air emissions data of Table 29 reflect a moderate (i.e., 80 per cent) efficiency attainable for collecting cadmium fumes and dusts from installations such as electric power generation stations and incinerators. These data also reflect the high (95 per cent or better) cadmium collection efficiencies attainable with installations specifically intended for relatively high flue gas concentrations of heavy metals, such as are found in zinc smelters, steel furnaces, and pigment calcining equipment.

Of the 300 metric tons per year of cadmium estimated to be the air emissions, the emissions from the primary zinc industry are 100 metric tons per year. Pyrometallurgical processes (with sintering operations) account for half the U.S. zinc production, and even with very efficient collectors, this large quantity of cadmium is lost. Any large reduction in this loss, short of abandoning the pyrometallurgical plants, would require unknown new technology to be applied to the flue gases. It must be remembered that the sintering operation is intended to purify the zinc calcine by volatilizing cadmium (and other impurities), and that the standard operating procedure is to recycle the collected flue dusts through the high-temperature processes in order to build up the cadmium concentration to where recovery is more economical.

Large total quantities of cadmium are also released to the air via combustion of fossil fuels and incineration processes. These quantities are large only because the quantities of fuels and solid waste burned are enormous; the cadmium is present only in trace concentrations.

By comparison to the water and air emissions, the data of Table 29 show that land-destined wastes contain much more of the cadmium released to the environment. Much of these cadmium-containing land-destined wastes are the residuals from air and water pollution abatement practices; the inter-media transfer has been especially important in the iron-and-steel industry, in electroplating, in pigment and battery manufacture, and in sewage treatment. Actually, even the cadmium released to the air and to water is transformed into land-destined waste via relatively rapid atmospheric fallout and via absorption onto river sediments.

The land-destined cadmium falls into two categories. The first category is made up of vast quantities of solid wastes, in which cadmium is only a very minor constituent. Included are the zinc ore tailings, the residues from coal combustion, incineration residues, and sewage sludge. The second category is made up of industrial wastes of much smaller total quantities and with much higher concentrations of cadmium; included are the residuals from electroplating, from pigment and battery manufacture, and the dusts collected from steel furnaces. Ways and means for either disposing of (in an environmentally adequate manner) or of recycling the industrial wastes of the second category are being developed and implemented. However, the enormous quantities of wastes of the first category imply that the near-term control strategy is the dispersing upon land of these wastes so as to prevent locally-high concentrations of cadmium (and other toxic substances).

Hence, for the land application of sewage sludges, phosphate fertilizers, zinc ore tailings, coal ash, incinerator ash, or other materials with cadmium concentrations significantly higher than those found in "normal" soils; the resulting cadmium content should not exceed the "natural" maximum of 0.6 ppm(93), which is an order of magnitude greater than the "typical" natural value of 0.06 ppm.

The application of cadmium-rich materials to soil is also dependent upon(96):

1. The soil pH. A pH of less than 6.5 makes cadmium much more available to plants.
2. The organic matter in the soil. Organic matter chelates the cadmium and makes it less available.
3. The cation exchange capacity of the soil. A soil with a high cation exchange capacity binds cadmium, and makes it less available.
4. The crop to be grown in the soil. Crops vary widely in their susceptibility to different toxic elements.

Dissipation vs. Emissions

The data of Table 29 may be analyzed from another viewpoint. Of the total estimated cadmium emission of around 2,000 metric tons per year, approximately 30 per cent (600 kkg/year) had its origin as primary cadmium metal. The emissions from zinc ore mining, beneficiation, and from zinc production amount to 20 per cent of the total emissions, and the remaining 50 per cent (and growing) are attributable to sources not associated with the primary zinc/cadmium industry (i.e., fertilizers, fossil fuels, and sewage sludge).

Hence, the emissions originating as primary cadmium metal are approximately 10 per cent of the consumption of primary cadmium. The converse of this statement is that the present situation of wide dissipation is 90 per cent effective in removing cadmium from circulation in an (apparently) environmentally adequate manner! Certainly the cadmium in plastics that are not incinerated remains bound in the resin matrix for a long time. The very good atmospheric corrosion resistance of cadmium leads to the conclusion that unless electroplated parts are subjected to an acidic environment, incinerated, or recycled as ferrous scrap, the cadmium remains immobile for a long time.

This argument does not, of course, relieve the concern for the 10 per cent that is emitted. Every prudent effort should be made to reduce this quantity. However, the control options must be thoroughly analyzed because there is a real danger of disturbing this balance and causing the remaining 90 per cent to become either more mobile in the environment or to be present in much higher (and much more hazardous) concentrations.

SECTION XIII

THE MARKET FOR CADMIUM

The market for cadmium differs markedly from the typical economic model of supply and demand responses to price changes for two reasons:

1. Cadmium Supply - Since cadmium is a by-product of zinc production, the supply is relatively insensitive to price changes;
2. Cadmium Demand - Since cadmium represents a small percentage of the total cost of most consumer products containing cadmium and since no adequate substitutes exist in many cases, even large price changes have little effect on demand.

This section contains supply and demand curves for 1974 and 1985 which are later used to estimate future cadmium discharges for the baseline situation (no regulation beyond present controls), and to estimate reductions in cadmium usage and cadmium discharges for a given cadmium regulatory alternative.

Cadmium Supply

Because there is no separate ore of cadmium, it is produced exclusively as a by-product material, either in the recovery of primary zinc from its ore or in the processing of secondary materials such as collected flue dusts and small quantities of secondary metal scrap. In addition, the General Services Administration, which had stockpiled cadmium from 1948 through 1963, has since been releasing significant quantities to industry. Cadmium supply statistics for recent years are listed in Table 30.

Figure 5 shows the U.S. cadmium supply as related to the price (in constant 1974 dollars). as Figure 5 indicates, the domestic supply of cadmium is inelastic, i.e., relatively insensitive to price level,

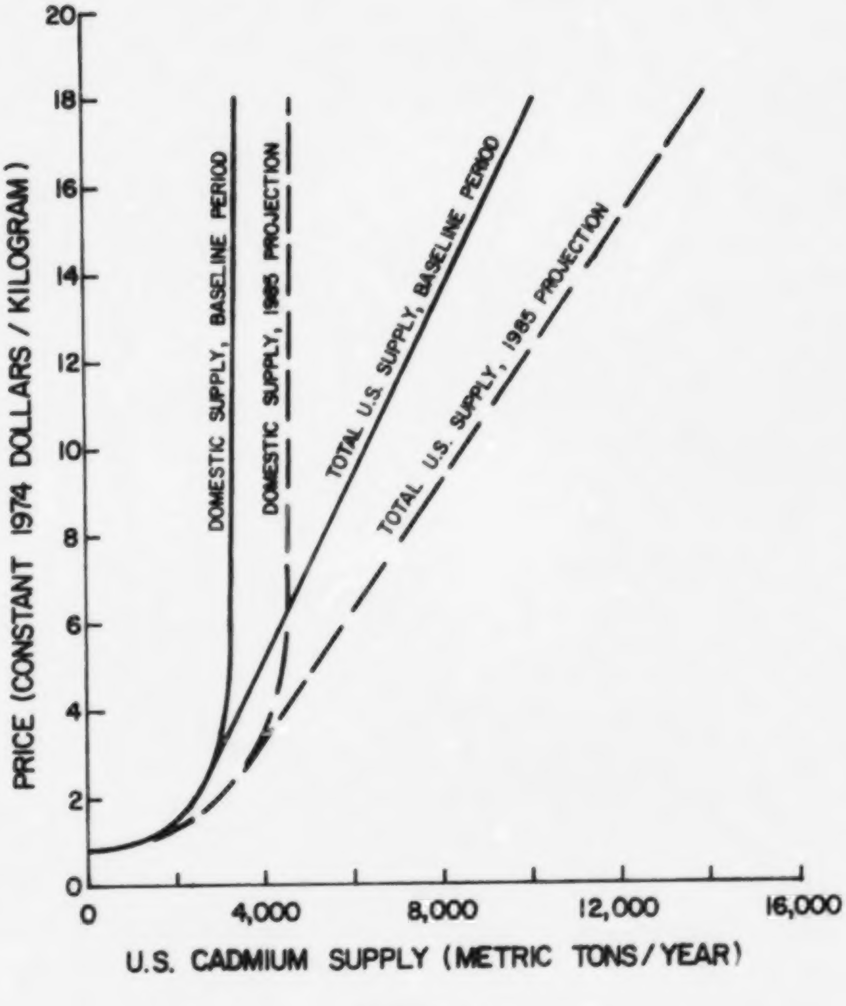

FIGURE 5
U.S. CADMIUM SUPPLY

TABLE 30

SUPPLY STATISTICS FOR CADMIUM

DATA IN METRIC TONS PER YEAR

SOURCES: BUREAU OF MINES[14,15,16,43]

	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
U.S. Refinery Production	4,540	4,710	4,410	4,710	3,940	4,830	5,740	4,300	3,600	3,760	3,370	3,180
World Production	11,800	12,700	11,900	13,000	13,070	15,010	17,580	16,530	15,550	16,600	16,920	17,000
U.S. Imports of Metal for Consumption	450	501	963	1,525	720	874	489	1,130	1,590	1,100	1,763	1,720
U.S. Exports	595	652	33	172	314	241	492	169	30	461	138	27
Shipments from GSA Stockpile	881	458	0	167	468	366	1,250	3	0	435	360	913
GSA Stocks	7,319	6,861	6,861	6,694	6,226	5,860	4,610	4,610	4,610	4,170	3,830	2,920
U.S. Production + Imports ≡ U.S. Supply	4,990	5,211	5,373	6,235	4,660	5,704	6,229	5,430	5,190	4,860	5,133	4,900
Avg. Price (Constant 1974 Dollars), $/kg	8.25	10.85	9.27	8.45	8.88	8.56	10.10	10.44	5.34	7.14	9.25	9.01

above a price of $5 per kilogram. Since cadmium is a minor by-product of zinc production (0.5 per cent of the quantity and 5 per cent of the value of shipments), the cadmium domestic supply is intimately related to the zinc supply and is relatively insensitive to cadmium price changes.

As Table 30 indicates, the world production of cadmium is in the range of 17,000 metric tons per year (of which about 13,000 is free-world production). The total U.S. supply curve (defined as U.S. production plus imports) has been constructed with considerable price elasticity, reflecting that there is an active world market in cadmium.

Without the benefit of an independent evaluation of cadmium production costs, it appears (assuming the recovery of cadmium-rich flue dusts and sludges is a requirement of zinc purification and pollution abatement regulations regardless of the market for cadmium) that the extra costs for cadmium recovery and refining should be no more than $2 per kilogram. This is based on the prices for zinc, lead, and copper, (all within $1.50/kg), and the basic similarities between the refining process for all of these nonferrous metals. The conclusion reached is that the price for cadmium is 3 to 5 times the production costs, so that the quantity produced is not closely correlated to price.

The corollary of this argument is that the supply would become elastic at prices less than $2 per kilogram. For this reason, the supply curve of Figure 5 has been extrapolated below $5 per kilogram in the manner shown.

Assuming an annual increase in the world's zinc production of 3 per cent,(15) and assuming that some additional secondary cadmium would become available in the U.S. (because of pollution abatement and reclamation) the 1985 supply would be about 40 per cent higher than the 1974 supply. The projected supply curve is also shown in Figure 5, with the understanding that this projection should reflect the uncertainty about the level of zinc production, cadmium recovery efficiency, extent of reclamation, and other unknown variables.

Cadmium Demand

Table 31 lists the cadmium demand statistics for recent years, as published by the Bureau of Mines.(14,15,16,43) Included is a BOM projection for the 1985 demand level. Although some minor inconsistencies exist between these BOM historical data and the data included in the earlier sections of this report (which incorporated other sources), the study of cadmium demand in this section is based upon the BOM historical data. However, the BOM projection for 1985 was not entirely adopted because of the following two points of disagreement:

1. BOM projects the battery demand for cadmium to conform to that of the GNP growth rate, 4 per cent. The discussion in Section VII of this report results in a projected growth rate of 15 per cent.
2. BOM projects the cadmium demand for PVC heat stabilizers to conform to that of the GNP growth rate, 4 per cent. The discussion in Section VI of this report projects FDA extensions of cadmium restrictions, the use of multi-screw extruders to reduce the temperature-time history, and the development of calcium-zinc stabilizers with equivalent performance and costs. Hence, a 4 per cent growth rate is not justified. The projection used in this study is of zero growth in demand to 1985.

TABLE 31

U.S. DEMAND STATISTICS FOR CADMIUM DATA IN METRIC TONS PER YEAR (ELEMENTAL CADMIUM)

SOURCES: BUREAU OF MINES(14,15,16,43)

	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1985
Electroplating	2,860	1,990	2,450	3,680	2,990	3,550	3,960	2,050	2,460	2,860	2,720		4,850
Pigments	1,560	1,180	1,160	910	500	610	660	590	700	860	1,010		950
Heat Stabilizers	360	340	390	1,080	1,000	1,140	1,220	1,080	1,290	1,130	900		2,360
Batteries	180	210	280	230	180	180	230	140	160	410	570		590
Other	170	210	410	640	350	360	430	250	300	460	450		810
Total U.S. Industrial Demand	5,140	3,930	4,690	6,540	5,020	5,850	6,500	4,110	4,910	5,720	5,650	6,300	9,560
Avg. Price (Constant 1974 Dollars), $/kg	8.25	10.85	9.27	8.45	8.88	8.56	10.10	10.44	5.34	7.14	9.25	9.01	

The demand schedules used in this study are as follows:

	1968-1972 Baseline kkg/year	1985 Projection kkg/year	Growth Rate Per Cent Per Year
Electroplating	3,100	4,850*	3
Pigments	700	950*	2
Heat Stabilizers	1,170	1,170	0
Batteries	230	2,200	15
Other	390	810*	5
Total	5,590	9,980	3.9

*BOM Projections

As is apparent, the total projected industrial demand for cadmium in 1985 is not very different, regardless of whether the BOM projections or the projections of this study are used.

Four uses - electroplating, plastic stabilizers, pigments and Ni-Cd batteries - are responsible for 95 per cent of the cadmium consumed annually. The means by which cadmium is supplied to the users are varied. Much of cadmium is bought by consumers who buy enough to deal directly with the smelter. In the electroplating industry, however, many of the chemical manufacturers who supply plating shops with the necessary chemicals act as distributors, purchasing large quantities of cadmium from the smelter and selling it to the platers along with their chemicals. Some of these "middlemen" import cadmium and distribute it in like fashion. In addition, GSA has supplied cadmium in recent years through its authorization to decrease the stockpile of cadmium; many distributors and large users of cadmium have purchased the excess reserves from GSA rather than from smelters. However, the GSA inventory as of November 30, 1974, was 2,920 metric tons, compared to a stockpile objective of 2,010 kkg; leaving an excess of only 910 kkg.

In order to develop a demand curve, the effects of price changes on demand must be examined. The demand for cadmium is a derived demand in each industry; it is the demand for the final good containing cadmium which causes the producer of that good to purchase cadmium. Therefore, the effect which a change in the price of cadmium has on demand will be a result of two effects:

1. the demand response to changes in the price of final goods as a result of changes in the cost of cadmium contained in them; and
2. the substitution of other materials for cadmium as the price of cadmium changes.

In all of the final goods, the cost of cadmium is such a small fraction of the cost of the total good that a 2 to 3 fold change in the price of cadmium should cause only a slight shift in the supply curve for a final good and hence a slight decrease in demand. However, the same change in price, while not affecting demand for the final good, may greatly affect the demand for cadmium in that final good if an adequate substitute exists.

Figure 6 shows the baseline (i.e., 1968-1972) cadmium demand curves for each of the major uses, drawn from the data of Table 31). As the data of Table 31 indicate (by inspection), the quantity of cadmium consumed for each use is not strongly correlated to the cadmium price. The following correlation coefficients were calculated for the 1968-1972 data:

Cadmium for electroplating	0.24
Cadmium for pigments	0.40
Cadmium for heat stabilizers	0.60
Cadmium for batteries	0.22
Cadmium for other uses	0.04

Hence, for all except pigments and heat stabilizers, the regression of quantity upon price accounts for less than 10 per cent of the variance in quantity consumed, and so the demand curves in Figure 6 were drawn vertically

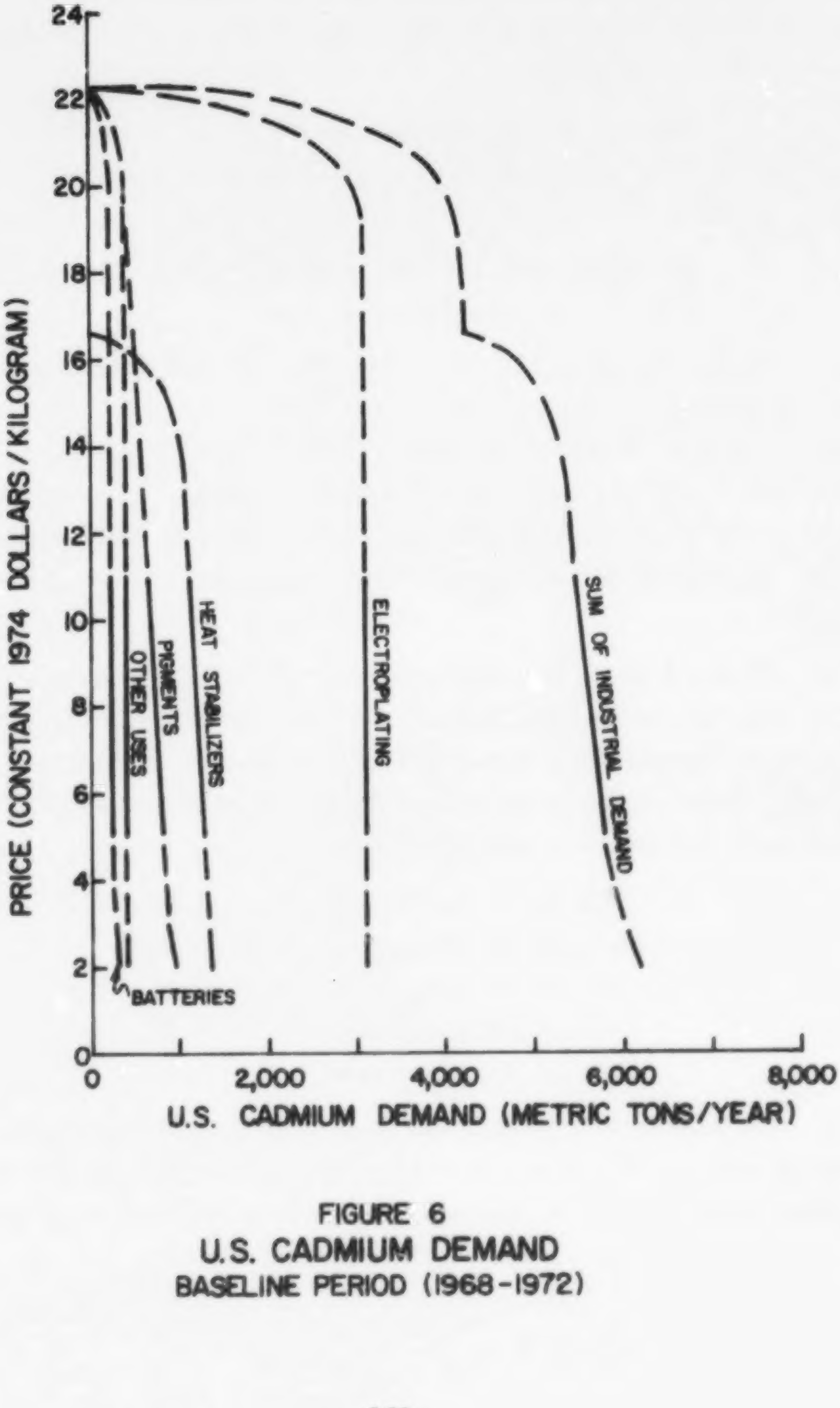

FIGURE 6
U.S. CADMIUM DEMAND
BASELINE PERIOD (1968-1972)

(e.g., completely inelastic demand) in the range of the historical data ($5 to $11 per kilogram). For both pigments and heat stabilizers, the demand curves of Figure 6 in this price range were drawn with the least-square slopes of the historical data, which are each about -25 metric tons per year/dollars per kilogram. The total cadmium demand curve of Figure 6 is the sum of the individual demand curves.

The individual demand curves of Figure 6 were extrapolated based upon the relevant discussions in previous sections. For electroplating, the costs (exclusive of metal costs) are in the range of $2.70 per square meter. The cost of cadmium is an additional $0.55 per square meter, while the cost of zinc is about $0.05 per square meter. The electroplating demand curve of Figure 6 was drawn with very little elasticity below the range of data; even if the cadmium price was $2 per kg rather than $8 per kg, cadmium would still be much more expensive than zinc and substitution for zinc should not occur. At the upper end, the curve shows no elasticity since those substitutions for cadmium on the basis of metal cost have already been made (i.e., cadmium at the present price of $8 per kg is already much more expensive than zinc). As the cost of cadmium reaches $20 per kg, however, the total plating costs become 50 per cent higher, and discussions with industry personnel indicate that demand would drop off at this level.(107)

Cadmium pigments are economically similar to the case of cadmium electroplating. These cadmium pigments cost $13 to $25 per kg, and even the lithopones cost $6 to $10 per kg; compared to chrome colors at $1.50 to $2 per kg and to iron oxides at less than $0.50 per kg. The demand curve of Figure 6 was constructed with some elasticity at $2 to $3 per kg of cadmium, reflecting a potential use of cadmium pigments at that price level instead of chrome colors. Since cadmium pigments are presently much more expensive than potential substitutes, little elasticity in demand was projected as the cadmium price rises even more. As a level of $20 per kg of cadmium is reached, however, industry sources indicate a drop in demand (probably by substituting other colors for the yellows, oranges, reds, and maroons).

The heat stabilizers curve of Figure 6 shows a different situation, however. The barium-cadmium heat stabilizers are already the cheapest and enjoy 50 per cent of the market, so that an even lower cost of cadmium should not greatly increase the demand. Calcium-zinc stabilizers are presently twice as expensive, so a drop in cadmium demand is projected at about \$15 per kg of cadmium, where significant substitution should occur not only from the Ca-Zn system but also from the organotins.

The batteries demand curve of Figure 6 has been drawn to be highly inelastic. In 1972, the quantity of cadmium used in batteries (410 kkg) was 10 per cent of the total quantity of nickel-cadmium batteries produced (4,600 kkg). The value of the cadmium, at \$8 per kg, amounted to \$3.3 million, which was 7 per cent of the total value of shipments for the batteries, \$47.6 million. Hence, the impact of cadmium price should be relatively minor below \$20 per kg of cadmium.

The total industrial demand curve is the sum of the individual demand curves; this is also shown in Figure 6.

In developing the baseline demand curve, all variables except price and quantity were held constant. From an examination of cadmium demand, it is apparent that many other variables affect demand. For instance, if a new battery were developed to replace the Ni-Cd battery, the curve would shift to the left and if a new use for cadmium pigments was developed, the curve would shift to the right. If a substitute stabilizer was developed, the shape of the curve might change or it might shift depending upon its price and adequacy as a replacement. Changes in uses of cadmium and cadmium containing products, availability of substitutes for cadmium and cadmium containing products, and the relative prices of cadmium-containing products and their substitutes, are all of prime importance in determing the shape and position of the demand curve.

For all uses except heat stabilizers, the 1985 demand projections shown in Figure 7 were developed by shifting the curves of Figure 6 according to the ratio of the projected demand levels (listed previously) to the baseline demand levels. For heat stabilizers, it is projected that other systems will be directly competitive from a cost standpoint, resulting in a much more elastic demand curve for cadmium in this industry. The total industrial demand curve of Figure 7 was obtained by summing the individual curves.

Relation of Supply and Demand

Figure 8 combines, on one graph, the baseline and projected supply curves of Figure 5 and the baseline and projected total demand curves of Figures 6 and 7. The projected 1985 cadmium consumption is 9,100 metric tons per year (an increase of 60 per cent over the 1968-1972 market) and the projected 1985 equilibrium price is $10.80 per kilogram (in constant 1974 dollars). This price is higher than the 1968-1972 price of $8.50 because the projected demand is greater than the projected supply relative to the baseline market.

It must be emphasized that these projections are not at all precise; both the projected supply curve and the projected demand curve could be shifted.

The development of a substitute or a price change for a final good containing cadmium will cause a shift in the entire demand curve; a new substitute for cadmium as a factor of production or a change in the relative prices of cadmium complements and substitutes will cause a change in the shape of the curve.

The unknown variables with the greatest effect on the results are:

Supply:
1. price of zinc
2. growth in zinc production
3. impediments to foreign trade
4. recovery from secondary sources

Demand:
1. technological change (i.e., a new substitute or a new use for cadmium)

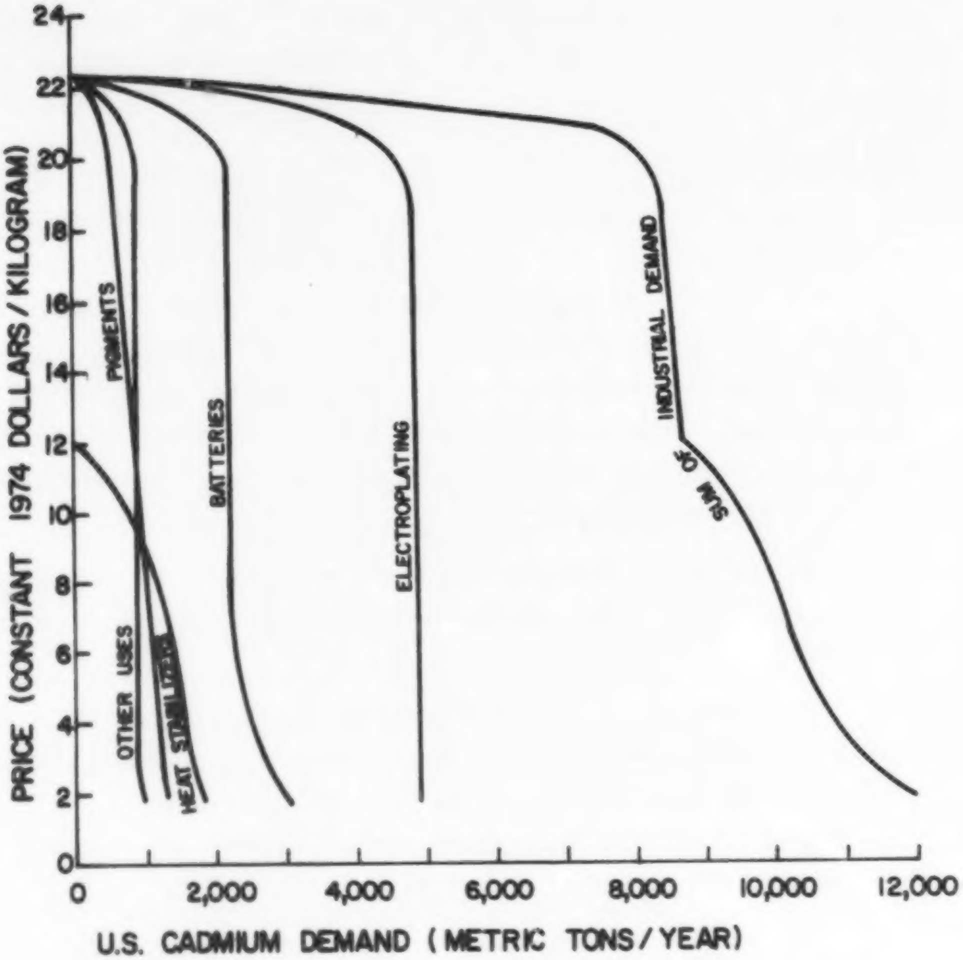

FIGURE 7
U.S. CADMIUM DEMAND
1985 PROJECTIONS

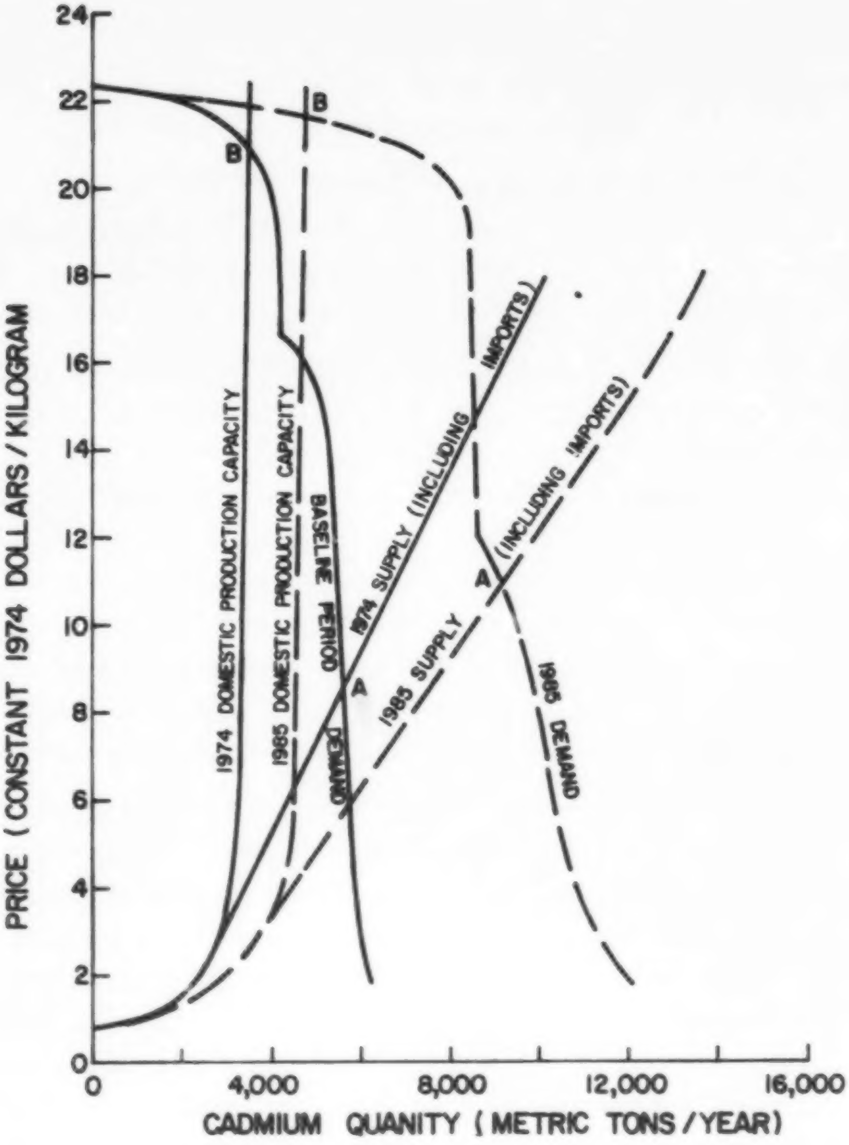

FIGURE 8
CADMIUM SUPPLY AND DEMAND

2. changes in the prices of substitutes and complements for cadmium and cadmium containing products
3. changes in the demand for cadmium containing products

In the baseline period, the domestic cadmium production (3,300 kkg/yr) satisfies 60 per cent of the U.S. cadmium demand. Based upon the projections of Figures 5, 7, and 8, the 1985 domestic cadmium production (4,600 kkg/yr) would satisfy only 50 per cent of the domestic demand (9,100 kkg/yr).

An informative exercise is the evaluation of the potential change in the domestic cadmium supply by the maximum recovery of cadmium from secondary sources. The incentive for such recovery (in addition to the environmental pressures for removing cadmium from products and residues) might be the projected increase in cadmium price to $10.80 per kilogram. Table 32 outlines the estimates (based upon the emissions of Table 29) for maximum recovery of secondary cadmium. The potential exists, then, for increasing the domestic cadmium supply, by 2,400 kkg per year from secondary sources, to a total of 7,000 kkg per year. At this level, only about 35 per cent of the U.S. cadmium demand would be satisfied by imports.

While batteries should consume about 25 per cent of the total cadmium by 1985 (as Figure 7 shows), the data of Table 32 shows that more than half of the reclaimable cadmium from secondary sources is from used batteries. In 1985, the value of the cadmium in batteries would be about $17 million per year, which should provide incentive for industry to develop institutional mechanisms for reclamation (the technology is already developed). In actuality, the nickel values from nickel-cadmium batteries provide a greater return than the cadmium. At least one manufacturer of nickel-cadmium batteries has already begun to encourage recycle by labeling and other inducements. It appears, then, that there will be sufficient

TABLE 32

ESTIMATES FOR MAXIMUM RECOVERY OF SECONDARY CADMIUM IN 1985

Source	Recoverable Quantity, kkg/year	Basis for Estimates
Primary Zinc Industry	80	Increase dust collection efficiency to 99 per cent
Electroplating Shops	80	Reclaim wastewater treatment sludges
Pigment, Stabilizer, Alloy, and Battery Manufacture	40	Increase dust collection efficiency and reclaim wastewater treatment sludges
Used Batteries	1,500	Recycle 75 per cent of used batteries
Secondary Metals	350	Process flue dusts
Galvanized Products	150	Use higher-grade zinc for galvanizing and recover the cadmium at the zinc smelter
Zinc Oxide	15	Recover cadmium in ZnO manufacture
Phosphate Fertilizers	130	Remove cadmium from phosphoric acid with new technology
Coal	50	Recover cadmium in coal gasification and liquefaction processes
Total	2,395	

incentive in the private sector to reclaim much of the cadmium from batteries. The government's posture should be one of encouragement of such reclamation.

The use of cadmium in batteries offers far greater potential for recovery of the cadmium than any other present use. Conversely, all other present uses are inherently dissipative; and therefore of prime concern from the standpoint of health hazards. If 75 per cent of the cadmium in batteries was recycled in 1985, the imports of "new" cadmium would be reduced from 4,500 kkg per year to 3,000 kkg per year.

Control Alternatives Based Upon Supply and Demand

One external market force to be considered is a tax and import duty on cadmium production and/or use. As previous discussions have indicated, however, the domestic cadmium demand curve is highly inelastic until the price reaches perhaps $20 per kilogram. Hence, a tax must be very high indeed before it becomes effective in curbing demand. As Figure 8 shows, the projected increase in cadmium consumption is not accompanied by lower prices; if this were the case, then a tax might be effective in the elastic region of the demand curve. However, in light of the consumption and price projections, a tax is not suitable for this situation.

An alternative control option is a quota on cadmium imports, or carrying it to the extreme, a ban on cadmium imports. Since the present level of imports accounts for 40 per cent of the U.S. cadmium demand; and since the projected level of imports would account, in 1985, for 33 to 50 per cent of the U.S. cadmium demand (depending upon the extent of reclamation of secondary cadmium); a partial or full ban on imports should be an extremely effective means for reducing the quantity of cadmium consumed in the United States. It is not anticipated that the domestic supply would increase appreciably in reaction to such an import restriction. Despite the importance of cadmium revenues to the zinc industry, cadmium has not in the past been a determining factor for deciding whether a zinc (or copper-zinc or lead-zinc) ore is economical, or whether a new primary zinc plant should be built.

With a total ban on cadmium imports, the 1974 domestic supply would be equivalent to the domestic production capacity, 3,300 kkg/year, and would be highly inelastic (as Figure 5 shows). At this quantity, the market price would be around $21 per kilogram, according to the baseline demand curve of Figure 8. Hence, the domestic producers may benefit from an extra revenue of $41 million per year. This excess may be scrutinized by the government in terms of an excess profits situation, in terms of compensating for the imposition of stringent emission controls and of possible product and byproduct quality regulations upon the primary zinc/cadmium industry, and in terms of making domestic zinc more competitive in the world market.

In 1985, the domestic supply with a total ban on imports would be at least 4,700 kkg/year (the projected domestic primary cadmium production capacity). At this quantity, the estimated market price (according to Figure 8) would be $21.60 per kilogram in the absence of an import ban. This would generate $51 million per year in extra revenue for the domestic cadmium producers.

However, Table 32 indicates that another 2,400 kkg per year of secondary cadmium is potentially available in 1985. The very high price for cadmium resulting from an import ban would serve to encourage reclamation. Batteries would have the largest potential (as Table 32 shows), but there should be strong incentives for reclaiming cadmium from flue dusts, industrial sludges, and even from phosphoric acid and coal. Such reclamation would only partially make up for the decrease in domestic supply brought on by an import ban. Table 33, which summarizes the estimated effects of several assumed levels of secondary cadmium recovery, shows that the market price would be above $20 per kilogram regardless of the fraction recovered. At this price level, the various cadmium consumers would be expected to develop and use substitutes.

In order for an import ban on cadmium to be effective, it must cover not only metallic cadmium, but also cadmium-bearing flue dusts, sludges, and other residues from abroad. Moreover, it must cover products derived from cadmium, such as electroplated parts, pigments, heat stabilizers, and batteries.

TABLE 33

EFFECTS OF SECONDARY CADMIUM RECOVERY IN 1985
(WITH A TOTAL BAN ON CADMIUM IMPORTS)

Fraction of Potential Actually Recovered	Recovered Quantity, kkg/yr	Total Domestic Supply kkg/yr	Market Price, $/kg
0.0	0	4,700	21.60
0.25	600	5,300	21.40
0.50	1,200	5,900	21.30
0.75	1,800	6,500	21.10
1.00	2,400	7,100	20.80

In addition to reducing the cadmium consumption level, an import restriction or ban would also serve to encourage secondary cadmium recovery from domestic sources. The market price of $20 per kilogram should be a very real incentive not only for reclamation of battery cadmium, but also for the various other sources listed in Table 32.

Another alternative control option for reducing cadmium consumption would be a ban (either total or selective) upon the use of cadmium. Figures 9 and 10 were constructed to (respectively) estimate the baseline and 1985 demand curves resulting from hypothetical selective bans on each of the uses in turn. The estimated equilibrium price, the total U.S. consumption of cadmium, and quantity of cadmium diverted for each selective ban, are summarized in Table 34.

Prompting Significant Reductions in Cadmium Demand for Electroplating

An alternate control strategy to a ban on cadmium electroplating is a reduction in the supply and demand for cadmium electroplating. The supply of cadmium electroplating may be reduced since stringent effluent guidelines would force some platers to cease this activity. This may be especially true for job platers whose present cadmium business is only a minor fraction of their total output, or for captive platers who can convert to alternate finishes.

On the demand side, cadmium electroplating has been distributed among the following end items:

End Use	Per Cent	kkg/yr
Industrial Fasteners & Other Uses	32.8	1,020
Electronics and Communications	26.3	820
Aircraft, Aerospace, Shipbuilding, Ordnance	20.5	640
Automotive Parts	20.4	630

TABLE 34

ESTIMATED EFFECTS OF BANS ON CADMIUM USE

	Cadmium Use Ban Assumed	Equilibrium Price, $/kilogram	Total Consumption Metric Tons/Year	Cadmium Diverted Metric Tons/Year
Baseline Period	None	8.50	5,600	0
	Batteries	8.00	5,400	200
	Pigments	7.10	4,900	700
	Stabilizers	6.20	4,500	1,100
	Electroplating	3.00	2,900	2,700
	All	-	0	5,600
1985	None	10.80	9,200	0
	Batteries	8.60	7,600	1,600
	Pigments	10.00	8,600	600
	Stabilizers	10.20	8,700	500
	Electroplating	5.50	5,500	3,700
	All	-	0	9,200

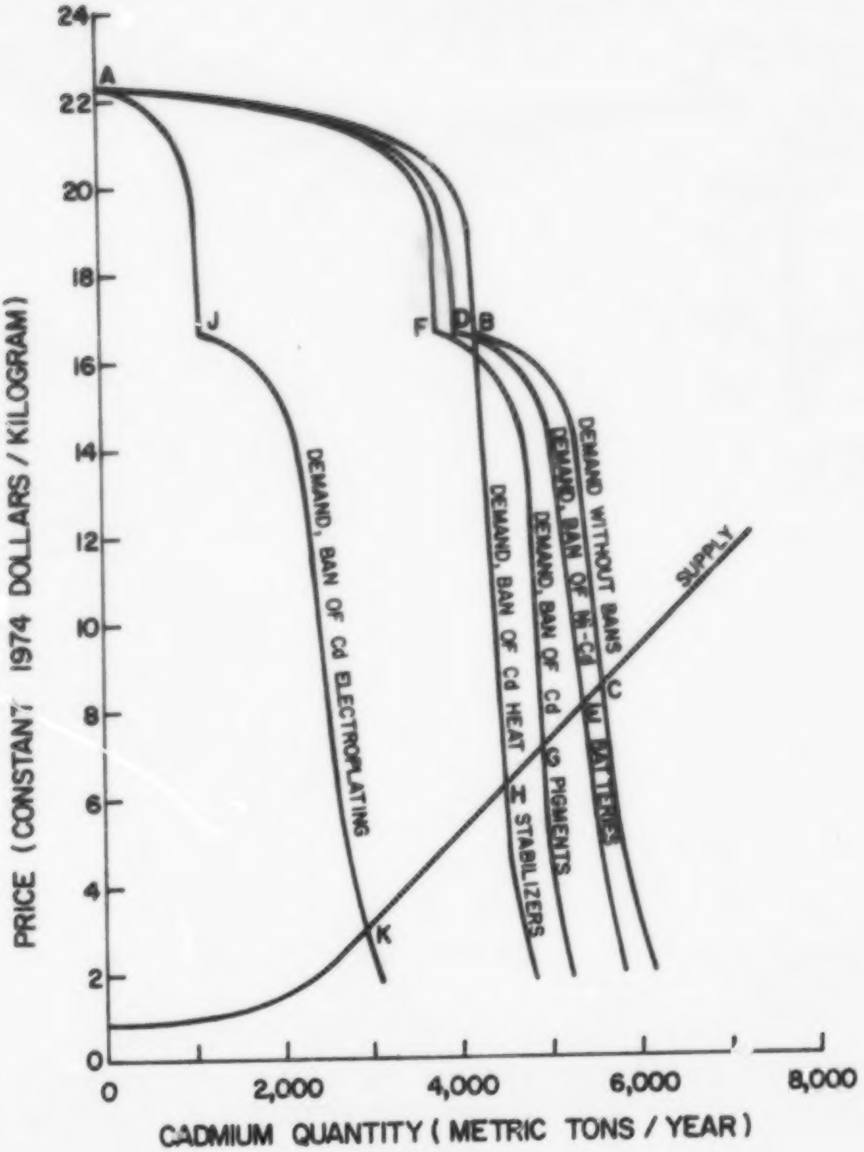

FIGURE 9
ESTIMATED EFFECT OF BANS OF CADMIUM
BASELINE PERIOD (1968-1972)

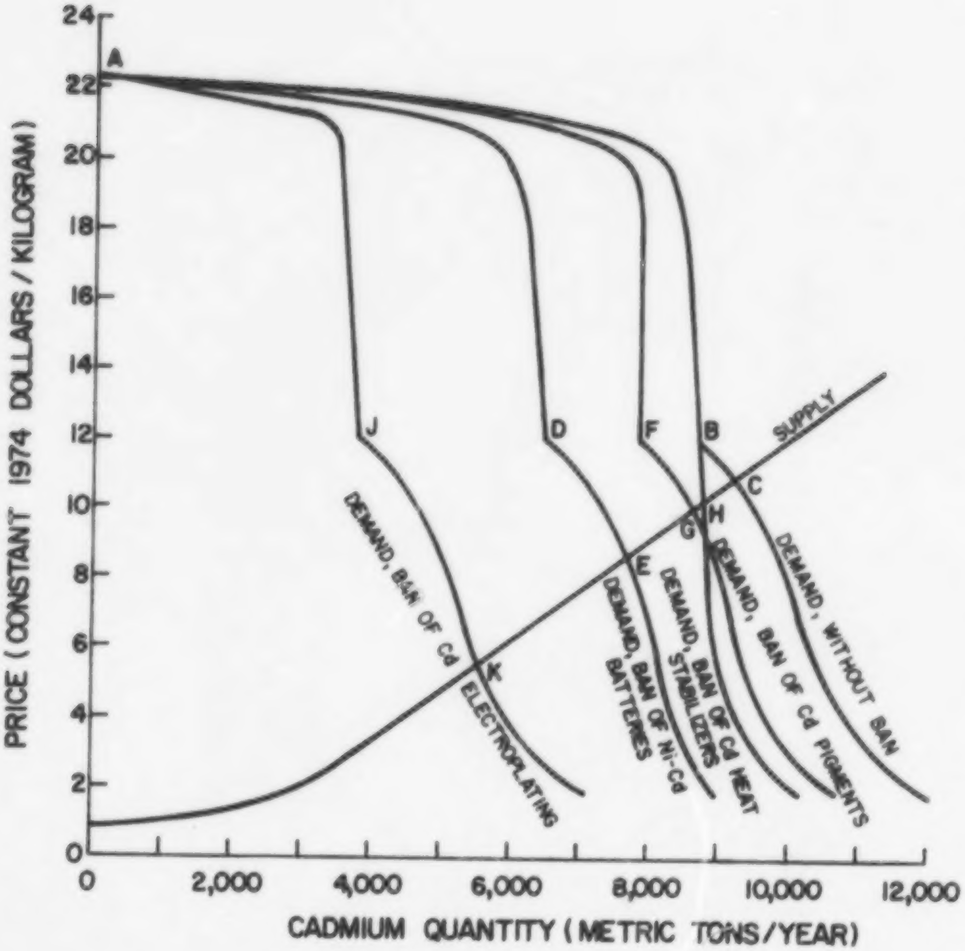

FIGURE 10
ESTIMATED EFFECT OF BANS OF CADMIUM
1985 PROJECTIONS

In addition to the cadmium electroplating demand of the automobile industry, some cadmium-copper alloying stock has been used in radiators, cadmium pigments are used for the plastics, and cadmium heat stabilizers are used for vinyls used in interior and exterior moldings and in calendered stock for coverings. It was previously shown that the recycling ratio for automobiles (as ferrous scrap) is much higher than for most other cadmium-using end items, and that a very large fraction of the No. 2 bundles of ferrous scrap is automotive scrap.

An alternative control strategy to regulation of the automobile manufacturing industry is to seek the voluntary cooperation of this highly-concentrated industry (with respect to the small number of prime domestic producers).

Falling into a similar category are the electronics, aircraft, aerospace, shipbuilding, ordnance, and similar industries, which to a large extent are suppliers of government (including military) requirements. Perhaps one main reason for the high inelasticity of demand for cadmium plating (and therefore for all cadmium) is simply the built-in inertia against change of longstanding, self-perpetuating, and intransigent government specifications. The military specification for surface treatments and inorganic coatings for metal surfaces of weapon systems, MIL-S-50002C, lists many alternatives to cadmium plating, but states that zinc may not be used for aerospace and missile systems due to its bulky corrosion products. A great many hardware and components military specifications call for the use of cadmium plating. Much may be accomplished in reducing these demands for cadmium electroplating. The Department of Defense specifications preparation activity is vested in two groups, the Defense Electronics Supply Center (for electrical connectors and electronics) and the Defense Industrial Supply Center (for fasteners and other mechanical parts). Hence, the organization exists for reviewing military specifications calling for cadmium-plated parts, to justify such specifications against alternate means for metal finishing.

It should also be feasible for a review and justification of specifications to be conducted by the aircraft, shipbuilding, electronics, and similar industries, all large consumers of cadmium electroplating. They are all highly structured industries (with relatively few major prime contractors, with a well-established hierarchy of subcontractors, and with a well-established formality of rigid specifications). Furthermore, much of the cadmium plating in these industries is captive.

Further study is required of the quantitative potential for significantly reducing the demand for cadmium without the requirement of a formal ban.

SECTION XIV

COSTS OF ALTERNATIVE REGULATIONS

In previous sections, alternatives for controlling various discharges of cadmium into the environment have been identified. In this section the costs associated with these alternatives will be quantified. In each case, the estimated cost is the difference between the course of events when no action is taken and the course of events given a specified cadmium regulation.

The costs of a control alternative can be broken into two broad categories: (1) long-run costs are derived from the differences between the two "steady states", one without a control alternative and one with; these costs extend indefinitely. The short-run costs are those incurred while moving from the steady state without a control alternative to one with a control alternative; these costs have a termination when the steady state with a control alternative is reached. If an effluent guideline were adopted, then the purchase of treatment equipment is a short-run cost for once the machinery is in place the new "steady state" is achieved. The upkeep of the machinery is a long-run cost, however, for it will occur every year in the future.

A second important distinction among costs is that between those involving direct monetary outlays and those which are felt in other ways. If an effluent guideline were adopted, then the treatment equipment is an out-of-pocket expense, but if the quantity produced decreases as a result, then the foregone consumer surplus is a cost despite the fact that there is no direct monetary outlay.

The costs estimated for each control alternative are in terms of dollars per kilogram of cadmium diverted from dissipation via the use in question. It is tempting to assume that all cadmium diverted by a specified control measure is harmless. This is not necessarily true. The costs presented here represent the cost of having cadmium in one form rather than another. The flow of cadmium through the environment is much like the flow of blood through the body — closing one vessel or channel simply forces blood through another. If, for example, cadmium is no longer dumped into a stream, it will be deposited as landfill; if it cannot be used in electroplating, it can be used as a pigment or other alternative. The metal will be mined as long as zinc ore is mined; however, the network of dispersion can be affected by regulation. The cost estimates in this study represent the costs of altering this flow, not the costs of rendering the cadmium harmless.

A comparison of control options on the basis of dollars per kilogram of cadmium diverted is also potentially misleading unless recognition is made of the benefits to human health and to environmental quality from each such diversion. The eventual choice of control measures should ideally be based upon the cost per unit reduction in health damage. Although the correlation between quantities of cadmium emitted and health damage was discussed in Sections X, XI, and XII, the basis for a quantitative estimate of health damage does not yet exist. For the purposes of this section, therefore, the benefits of a control alternative will be assessed in terms of quantity of cadmium diverted from dissipation, with the results regarded as the results of a screening mechanism of candidate options. Without a more precise measure of health benefits, it is not possible to identify the most cost-effective options or to determine the amount of diversion societally desirable. The purpose of this section is to provide an indication of the available options, their likely effects, and the probable costs — important steps in selecting controls to be instituted.

The control options evaluated here are those which seemed most feasible in preliminary review. Many alternatives were considered and some were rejected for detailed analysis because the costs appeared too great for the perceived benefit on an a priori basis; others were rejected because their effectiveness was shown to be too small.

Costs of a Ban on the Use of Cadmium

A ban can be selective or all-encompassing. In this report, costs of banning the use of cadmium in each of the four major industries and in all uses will be considered. As has been pointed out, the costs can be broken most simply into two categories, long-run and short-run. An outline of the costs which can be applied to each case will be developed, but the way in which the costs arise will be explained first.

Most of the costs of a cadmium ban are those one would expect in any industry. However, due to the peculiarity of the cadmium market, certain unexpected costs are incurred. Because cadmium is produced solely as a byproduct, and because the quality requirements of the primary product (zinc) and emission regulations force the isolation of most of this byproduct, the cadmium supply is highly inelastic, i.e., highly insensitive to price (as Figures 5 and 8 show). Moreover, the marginal costs for refining cadmium (once it is isolated in dusts and sludges at appreciable concentrations) are likely much less than the market price for cadmium; it was earlier estimated that these marginal production costs are less than \$2 per kilogram, compared to a price of \$7 to \$11 per kilogram.

Since a decrease in cadmium demand resulting from a total or partial ban on its use will decrease sales and therefore revenues and profits to the smelters, the zinc industry would be affected by a ban, either selective or all-encompassing, on the use of cadmium. Approximately 4 kg of cadmium are refined from a metric ton of zinc in the production process which means \$40 in revenues are returned from cadmium sales for every \$800 in zinc sales. If the profit margin on zinc sales is assumed to be 10 per cent (or \$40 per metric ton), and if it is assumed that the profit margin on cadmium sales is \$5 per kilogram (or \$20 per metric ton of zinc), then the following illustrates the relative importance of cadmium to the zinc industry:

Cadmium quantity,	0.4	per cent of zinc quantity
Cadmium revenues,	5	per cent of zinc revenues
Cadmium profits,	25	per cent of zinc profits

It must be emphasized that the above comparison of profit is without any real basis in data or in substantive analysis. Of course, the method of allocating production costs would influence the comparison of cadmium and zinc profits; if the costs for removal of cadmium from zinc calcines and if a proportion of the mining, beneficiation, and roasting costs were charged to cadmium, then the profit comparison would be entirely different. However, the fact remains that a total ban on cadmium, resulting in stockpiling of cadmium dusts and sludges at primary zinc plants, would have a relatively large effect on the overall industry profit margin.

Through instituting a ban, society suffers a cost equal to the difference between the benefits which would be derived by producing the cadmium and the benefits which can result from using those resources in their next most productive capacity. The lowered level of production will free resources to move into other uses and idle capital and unemployment will result from their partial immobility. This is a short-run phenomenon resulting in short-term costs.

The primary cost of a ban is the foregoing of the benefits from cadmium usage, a long-run cost. If the market system is functioning properly, then the resources presently used to produce cadmium are being used in their most productive capacity, that is, they would produce fewer benefits if employed elsewhere. Therefore, by prohibiting a form of cadmium consumption one forces them into alternative production and suffers a cost equal to the difference between the benefits if used in cadmium production and the benefits if used elsewhere — the consumer surplus. The following subsection explains in greater detail the definition of foregone benefits and the techniques for their estimation.

Definition and Estimation of Foregone Benefits

Cadmium pollution can be reduced by control devices that prevent cadmium emissions or by a ban on cadmium uses. Whereas control devices involve extra cost in cadmium production or use, a ban on cadmium involves a cost in forcing people to use cadmium substitutes — forcing users to forego the benefits of cadmium over and above the next best substitute.

Although there are substitutes in virtually every use of cadmium, they are not perfect substitutes. Sometimes they cost more, sometimes they don't provide the same quality product, and sometimes they don't last as long. The mere fact that cadmium is being used verifies that it has advantages over the next best substitutes. It is possible that some uses are not justified at current market prices, but it is inconceivable that all uses are unjustified.

There is a question whether cadmium use would be justified (economical) if the cost of environmental damages were added to current market prices. This project does not include estimating cost of the environmental damage; however, it does include estimating the cost of a ban on cadmium use — one means to avoid environmental damage. The cost of a ban is the cost to society of foregoing the benefits of present and future cadmium use:

1. Benefits to users — the difference between market price and the value of cadmium in various uses.
2. Benefit to producers — the difference between market price and the cost of producing cadmium for the market.[a]

By estimating and adding the two foregone benefits we can determine the minimum environmental damage cost that will justify a ban on cadmium use.

Figure 11 is a simple market description illustrating foregone benefits from a ban which prohibits the Q_1 consumption of cadmium for, say, pigments. Users forego benefits equal to area P_2P_3A while producers forego benefits equal to area P_1P_2A. In other words, users pay only the P_2 market price, but the actual value/unit of cadmium to them is the average value on the demand curve between P_3 and A. Likewise, producers receive price

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[a] Since cadmium is a by-product and there can be disposal costs if it is not sold, the production cost must be calculated carefully.

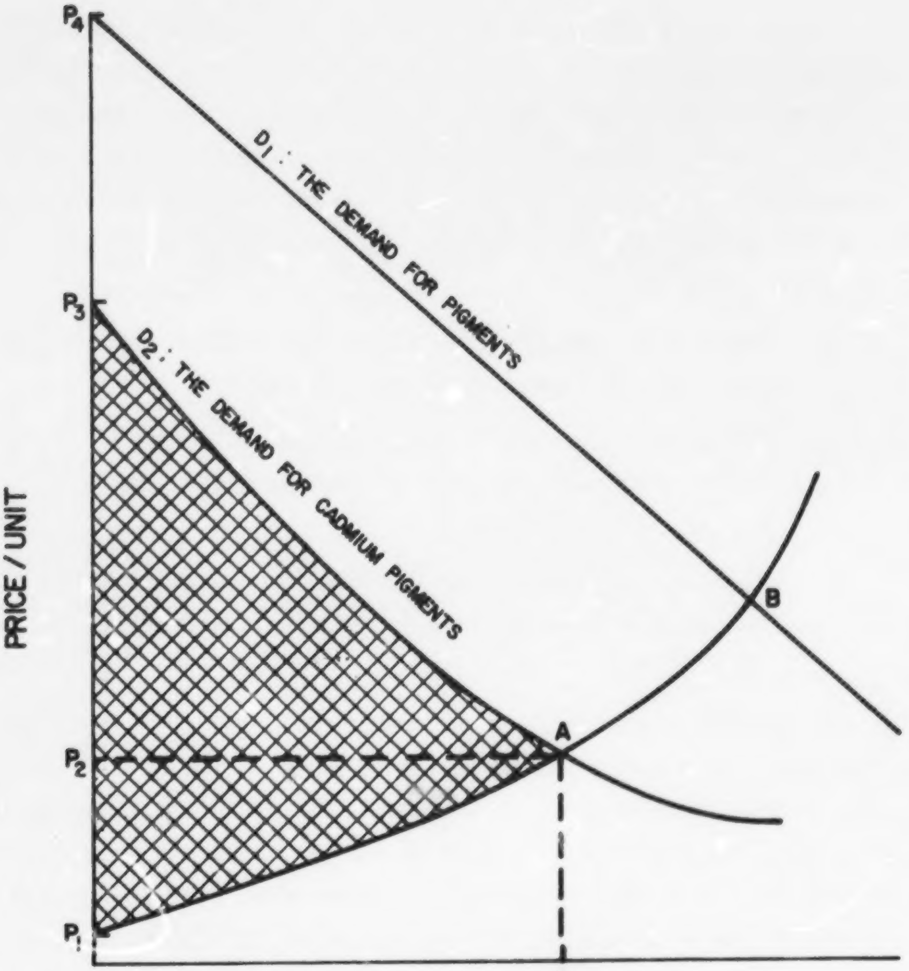
P4
P3
P2
P1
D1 : THE DEMAND FOR PIGMENTS
D2 : THE DEMAND FOR CADMIUM PIGMENTS
A
B
Q1
PRICE / UNIT
QUANTITY

FIGURE 11
FOREGONE BENEFITS

P_2, but the average cost/unit is only the average value on the cost curve between P_1 and A.

By determining the value of cadmium from demand curves, we automatically consider the possibility of cadmium substitutes. The difference between the D_1 specified demand for pigments and the lower D_2 demand for cadmium as a specific pigment reflects opportunities for substitutes. Stated otherwise, the foregone benefits to users from a ban on cadmium would be P_2P_4B instead of the smaller P_2P_3A if cadmium had no substitute.

There are two basic ways to determine foregone benefits to cadmium users and producers. One approach is an engineering analysis— an analysis that a user himself would employ in determining what he is willing to pay for cadmium and its substitutes, or that a producer himself would employ in determining how much to produce at each price. A second approach is to trace out the demand curve (e.g., the curve P_3A in Figure 11) from (1) observed changes in market prices and quantities and (2) opinions of experts among suppliers and consumers.

The estimates for this study were developed under the second approach. The first approach is very expensive and subject to significant errors from inaccurate or incomplete information.

Cadmium demand curves developed for this study indicate that substitutes for some uses are very good and, therefore, a ban would produce few foregone benefits. In other uses, substitutes are so inferior that the current \$7 to \$9 per kg market prices could increase to \$22 per kg and users would still prefer cadmium over substitutes. By definition, the cadmium user who would pay as much as \$22 per kg would forego a minimum of \$15 benefit per kilogram if the cadmium he can now purchase at \$7 per kg is banned.

The cadmium demand curve P_3A in Figure 11 is drawn to indicate that market price is nearly equal to consumer value for part of the uses, but consumer value is significantly above market price in other uses.

In the long run, foregone benefits are paid by the many consumers of products in which cadmium is a component. It is erroneous to think that the benefits of cadmium uses are obtained by a few producers acting against the public interest while the benefits of less cadmium pollution are to be enjoyed by the general public. In the short run, producers of cadmium and manufacturers that use cadmium in their products will suffer losses from a ban. However, in the long-run, suppliers reach a new equilibrium via zinc prices and the consumers bear the loss of foregone benefits via higher zinc prices and via higher prices or lower quality of products containing substitutes for cadmium.

Estimates of foregone benefits are certainly subject to error. However, they are often a significant cost to society whenever there is a ban on products for environmental or any other reason; therefore, foregone benefits must be estimated to provide a complete accounting of social costs and they must be analyzed if we expect to make rational decisions on cadmium controls. Estimates in this report are objective estimates of cost consequences of specified cadmium control alternatives.

Outline of Cost Elements

A. Long-Run

1. Foregone Benefits — If cadmium can no longer be used for a certain purpose, then society must forego the benefits in excess of the best alternative use of resources. The cost is equal to the amount society would have been willing to pay to have cadmium available for that purpose, the area under the demand curve, less the amount which would have been paid in alternate uses, the area under the marginal cost curve. This cost occurs each year the ban is operative.

   One factor which affects this cost is the development of new substitutes. Whereas the presently available substitutes are represented in the demand curve, new substitutes that could be developed are not included, even though they can reduce the cost significantly.

2. New Discharges — when cadmium is selectively banned from one industry it may be used in other industries which will result in new discharges. The magnitude of this cost depends upon the industry or industries which use the freed cadmium and how much they use. Since the estimation of foregone benefits already allocates the freed cadmium to alternate uses, the quantity of new discharges will be equal to the increment in consumption for each use. Hence, under the assumption of equivalent environmental damage per unit of cadmium dissipated (regardless of the mechanism or form of dissipation), no additional costs will result. For the case of a total cadmium ban, there is a priori no new discharge costs.

3. Disposal of Excess Cadmium — Since the quantity of cadmium in the zinc is fixed, when less cadmium is recovered, more cadmium is distributed elsewhere. In the long-run this quantity should be deposited as a secured landfill. It should be pointed out that, by placing a ban on a certain form of consumption, domestic demand is unlikely to fall by an amount equal to that form of consumption. As a result of decreasing domestic production and increasing domestic consumption, future slacks in demand are more likely to result in decreased imports than decreased domestic demand. Carried further, sufficient slacks in demand would result in exports

of primary cadmium. This aspect further confuses an estimate of this cost and the costs of new discharges.

4. Smelter Impact — Since a ban will decrease demand for cadmium, revenues to the smelter will decline and one might expect an impact on this industry. The comparison of zinc and cadmium quantities, revenues, and profits made previously (while having no real basis in fact or data) indicates that some increase in zinc price would be expected to make up for any lost cadmium revenues and profits. Without explicitly evaluating the zinc price increase or the long-run costs of such an increase; it will be assumed that the zinc price will increase about $0.02 per kilogram for a total cadmium ban, equivalent to the lost cadmium profits. Further, it will be assumed that this 2.5 per cent increase in zinc prices will not result in a significant decrease in domestic zinc consumption. If this domestic price increase is sufficient to cause a competitive disadvantage with respect to imported zinc, the U.S. could conceivably increase the import tariff from the present value (1/1/75) of $0.015 per kilogram to the statutory limit of $0.039 per kilogram.(15)

   For these reasons, then, the long-run smelter impact costs will be assumed negligible for the purposes of this study. The authors invite other estimates, however, in light of the gross and unsubstantiated assumptions made in this estimate.

B. Short-Run

1. Capital that becomes obsolete or reduces in value. If cadmium is not available for a specific production process, then either the capital will be used for other purposes in its present state, it will be converted for other purposes, or it will lie idle, depending upon the costs of conversion and the perceived productivity of the capital in a new function. The cost of a cadmium ban to society depends upon how much of the benefits which could have been provided by the existent capital can be reclaimed. By introducing a time lag between the announcement of a ban and its institution, these costs can be reduced significantly.

2. Unemployment — As a specific production is halted by a ban on cadmium, the labor involved in that production could become unemployed. The cost depends upon the amount of time unemployed and their productivity in new jobs relative to the old jobs. By introducing a time lag between the announcement of a ban and its institution, these costs can be reduced significantly.

3. Stockpiling — If the demand for cadmium is reduced, stockpiling is likely to occur as a short-run response. The cost is the opportunity cost of using the resources which go into stockpiling. The drop in demand will

result in fewer imports and a short-run stockpiling at the smelter for a ban on electroplating (where the total demand will be significantly reduced). For a total ban on cadmium, stockpiling would probably not occur since the smelters would have no reason to refine the cadmium to stockpile.

Because an estimate of the amount stockpiled is dependent on so many unknown variables, this cost will not be quantified. However, since the cost is probably small and it only exists in the short-run, this will not affect the results appreciably.

4. Lag Time for Substitutes — In considering the benefits foregone by the use of cadmium in specific areas, the benefits which can be provided by substitutes have been accounted for. However, these substitutes will not be readily available when the cadmium ban is effected. During the conversion to substitutes, the benefits from these substitutes are also foregone. The introduction of a time lag can reduce this cost also.

5. Miscellaneous — Depending upon the particular industry and use, there may be additional short-run costs. For instance, if Ni-Cd batteries are banned, further costs are incurred since these batteries are component parts of other consumer goods:

   - changing machinery producing these goods so that they can use another power source,

- converting the goods already produced to use another power source, and/or
- goods left unused because Ni-Cd batteries are not available and the costs of power conversion are too high.

These costs will not be estimated; in general, they will be insignificant when compared to the rest.

Using the above outline as a guide, the costs resulting from a selective ban on each of the primary uses of cadmium will be considered, as well as a total ban on all forms of cadmium consumption.

Foregone Benefits (Long-Run Costs)

Using the estimated cadmium demand curves of Figures 9 and 10, the foregone benefits for each ban was calculated as the area, above the supply curve, between the demand curve without bans and the appropriate demand curve for each ban. Hence, the foregone benefits for a ban on nickel-cadmium batteries is the area within ABCEDA; those for a ban on cadmium pigments is the area within ABCGFA; etc. The results are tabulated below in terms of the annual foregone benefits for each selective ban, and the foregone benefits per kilogram of cadmium diverted for each ban (the quantities of cadmium diverted are listed in Table 34).

Cadmium Use Ban Assumed		Foregone Benefits, Million Dollars/Year	Foregone Benefits, Dollars/kg Diverted
Baseline Period	None	0	-
	Batteries	3.3	16.70
	Pigments	7.4	10.60
	Stabilizers	9.3	8.40
	Electroplating	48.8	18.10
	All	92.2	16.40
1985	None	0	-
	Batteries	26.6	16.60
	Pigments	8.1	13.60
	Stabilizers	0.4	0.80
	Electroplating	64.3	17.30
	All	149.3	16.20

The foregone benefits for bans on batteries or electroplating, or for a total ban on cadmium use, are approximately $16 per kilogram of cadmium diverted from these uses. The foregone benefits from banning pigments are somewhat lower (approximately $12 per kilogram diverted) reflecting the slight elasticity in the pigment demand curves of Figures 6 and 7. Banning cadmium heat stabilizers would involve foregone benefits of $8 per kilogram in the baseline period, and less than $1 per kilogram in 1985, since substitutes are available at much lower price levels than substitutes for other cadmium-consuming commodities.

Disposal of Excess Cadmium (Long-Run Costs)

The 1974 domestic cadmium production capacity is 3,300 metric tons per year, and the projected 1985 capacity is 4,600 metric tons per year. Comparing these to the estimates of total consumption of Table 34 for assumed cadmium use bans results in the data of Table 35, the maximum estimates for the quantities and costs for disposal of excess cadmium. A unit cost for environmentally adequate land disposal (i.e., secured landfill) of cadmium-rich sludges or dusts was taken as $320 per metric ton of elemental cadmium in the waste (see Section VII). In lieu of estimating any

TABLE 35

ESTIMATED MAXIMUM COSTS FOR DISPOSAL OF EXCESS CADMIUM

Cadmium Use Ban Assumed		Excess Cadmium, kkg/yr	Cost of Disposal, Million Dollars/Year
Baseline Period	None	0	0
	Batteries	0	0
	Pigments	0	0
	Stabilizers	0	0
	Electroplating	400	0.12
	All	3,300	1.05
1985	None	0	0
	Batteries	0	0
	Pigments	0	0
	Stabilizers	0	0
	Electroplating	0	0
	All	4,600	1.47

excess quantities (of domestic production over domestic consumption) exported, i.e., an analysis of the world cadmium market, the maximum costs for disposing of excess cadmium are estimated by assuming no exports.

Idle Capital (Short-Run Costs)

In the nickel-cadmium battery industry, it is felt that if cadmium were unavailable, the existent plant and equipment would have no alternative uses and, therefore, a zero salvage value. This is probably an overstatement; buildings could surely be converted to another function at a certain cost; however, for purposes of this report, we shall consider the statement to be essentially true. Since machinery has a productive capacity which would not be utilized in any fashion, society foregoes certain benefits by allowing it to lie idle. The true loss is difficult to estimate since members of the industry are reluctant to divulge any pertinent data. Even the National Electrical Manufacturers Association, an organization which includes the battery manufacturers among its members, has been unable to obtain such data. A very crude estimate is possible, however.

One firm estimated the original cost of plant and equipment at $14 million. Since their annual sales are approximately 15 per cent of the Ni-Cd battery market, it is reasonable that the total original value of industry plant and equipment would be about $100 million. Considering that most of the productive capacity has been built in recent years, depreciation to date should not be large, and this figure seems a reasonable estimate of present value. If this present value is amortized over 15 years, the annual cost is $7 million per year.

A more precise estimate would be desirable, but the error should not affect the final cost estimate appreciably.

In the cadmium electroplating industry, state and federal effluent controls will probably create a trend towards concentration in fewer shops. At present, there appear to be many shops with only one cadmium bath — a small cadmium plating capacity. If effluent limitations are much more stringent for cadmium than for zinc, the additional cost would price most of them out of the cadmium plating market because there are larger operations which can spread the cost over a larger output. As an example, the job plating shop described earlier in this report plated cadmium on only 12 per cent of its work; it is possible that such a shop may elect to discontinue cadmium plating should effluent guidelines dictate segregation and separate treatment and recovery of cadmium wastes.

Although much of cadmium plating is manual barrel plating, the baths would likely be used (if cadmium plating were banned) for barrel plating of zinc, copper, nickel, chrome, or other metals. The idle capital costs due to a cadmium plating ban, therefore, should not be significantly higher than the idle capital costs resulting from stringent effluent guidelines. Hence, no separate costs will be attributed to banning cadmium plating.

The equipment used in manufacturing barium-cadmium heat stabilizers can be used to produce the substitute calcium-zinc stabilizers. Therefore, beyond some small transition costs, the costs of idle capital should be negligible.

The production process for cadmium pigments is unlike that of any other type pigment so their plant and equipment would have no reclaim value. Six companies manufacture cadmium pigments and the approximate cost of a "typical plant" is $5 million. The plant itself should last forty years and the production equipment 10 years. Assuming that half the value of the plant and equipment of the six companies has been used thus far, a cost of nearly $1 million per year for the next twenty years from idled capital would result.

Unemployment (Short-Run Costs)

As the capital is idled, labor is unemployed. Unlike capital, however, labor can find substitute employment and so the cost exists for a shorter duration. The same battery firm mentioned above, whose annual sales are approximately 15 per cent of the market, employs 400 persons. Based upon this employment-output rate, industry-wide employment is 3,000.

The average salary in the storage battery industry is $9,000 (1972 Census of Manufacturers, Preliminary Report). If the average length of unemployment caused by the ban were 6 months, the associated cost would be $13.5 million.

In the electroplating industry, some unemployment will probably occur if a ban is instituted; some shops will have to lay off workers while they find new demand to replace their cadmium contracts. Even if a shop replaces its cadmium plating demand with substitutes, it is possible that more highly skilled workers would be required (cadmium plating is a less critically-controlled operation). The unemployment or shifts in employees are likely to be short run, and of an insignificant magnitude compared to the costs already cited. The unemployment cost might become significant if many shops were to close, but as stated before, the costs over and above the costs resulting from stringent effluent guidelines would probably be small.

No significant unemployment costs (beyond some small transition costs) are expected for the heat stabilizers industry, where substitutes may be made by the same workers.

A "typical" cadmium pigments plant employs 15 hourly and 2 to 3 salaried employees. If their average annual salary were $10,000 and six months expired before alternative employment could be found, a cost of $85,000 would occur in the first year of the ban. For the entire industry (six companies), the unemployment costs in the first year would be $510,000.

Summary of the Costs for Banning Cadmium Use

Table 36 summarizes the costs for each selective ban and for a total ban on cadmium use. As Table 36 shows, the foregone benefits are the overwhelming costs for all except the battery industry (where idle capital and unemployment costs are large). The additional short-run costs for a total ban on cadmium would be (based upon an estimated 1975 cadmium consumption of 6,000 metric tons) $3.60 per kilogram for the first year and $1.30 per kilogram for each of the next 15 to 20 years.

TABLE 36

SUMMARY OF COSTS OF SELECTED AND TOTAL BANS

COSTS IN MILLIONS OF 1974 DOLLARS

Time Frame		Cadmium Use Ban Assumed				
		Batteries	Pigments	Stabilizers	Electroplating	Total Ban
1970	Long-Run Annual Costs:					
	Foregone Benefits	3.3	7.4	9.3	48.8	92.2
	Disposal	0	0	0	0.1	1.1
	Total	3.3	7.4	9.3	48.9	93.3
1985	Long-Run Annual Costs:					
	Foregone Benefits	26.6	8.1	0.4	64.3	149.3
	Disposal	0	0	0	0	1.5
	Total	26.6	8.1	0.4	64.3	150.8
	Short-Run Annual Costs:					
	Idle Capital Costs	7	1	0	0	8
	Duration, Years	15	20	-	-	15-20
	Unemployment Costs	13.5	0.5	0	0	14.0
	Duration, Years	1	1	-	-	1

Costs of Banning Cadmium Imports

The costs of an import ban were estimated in the same way as the costs of a use ban. The foregone benefits were calculated by integrating to the left of the total supply and demand curves (as they intersect at Point A on Figure 8), and subtracting the integral to the left of the domestic production and demand curves (as they intersect at Point B). These long-run costs are $24.4 million per year $11.10 per kilogram of cadmium diverted) for the 1985 time frame.

The short-run costs for the domestic cadmium-consuming industries would be approximately 40 per cent of those costs shown in Table 36 (since the decrease in consumption would be approximately 40 per cent of a total ban on each use):

	Cadmium-Using Industry				
	Batteries	Pigments	Stabilizers	Electroplating	All
Idle Capital Costs*	2.8	0.4	0	0	3.2
Duration, Years	15	20	-	-	15-20
Unemployment Costs*	5.4	0.2	0	0	5.6
Duration, Years	1	1	-	-	1

*Millions of Dollars Per Year

SECTION XV

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